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D-T AXICELL MAGNET SYSTEM FOR MFTF-α+T*

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Abstract: The configuration and design of the deuterium-tritium (D-T) axicell superconducting magnets for the Mirror Fusion Test Facility (MFTF-α+T) are described. The MFTF-α+T is an upgrade of the MFTF-B, with new end-plug magnets and a neutron-producing central D-T axicell section. The 4-m-long axicell — its length defined by the 12-T peaks in the mirror field — is beam fueled and heated by two beam lines, each with four neutral beam injection ports. Two large superconducting coils (mean diameter ~3.8 m) located at Z = ±2.40 m, in conjunction with a small copper coil located outside the test volume region, produce the 4.5-T mirror midplane field. This background field is augmented by two copper coils to create the 12-T peak mirror fields at Z = ±2 m. The central region of the axicell accommodates a 1-m-long, replaceable blanket test module. The length (4 m) of the axicell was chosen to provide relatively uniform neutron wall loading over the test module. In many respects, this axicell is less than full scale, but it could be viewed as a short section of a reactor, complete with the support systems and technologies associated with a mirror reactor.

The peak field at the superconducting coils is 10.8 T. The coils employ hybrid superconducting winding — Nb_3Sn conductor in the 8- to 12-T region and NbTi in the 0- to 8-T region. The winding is cryostable and is cooled by a 4.2 K liquid helium bath. The conductor design, the winding design, and the performance analyses for these superconducting coils are described.

Introduction

The MFTF-α+T is an upgrade of the MFTF-B with new end-plug magnets and a neutron-producing, reactor-like central D-T axicell section. The magnet system for MFTF-α+T consists of 32 coils; their design is described in Ref. [1]. The axicell magnets are required to provide a given axial field profile (B = 4.5 T at Z = 0 m, and B = 12 T at Z = ±2 m). The magnet system must be compatible with other subsystems (e.g., the neutral beams and test module). A trade study was made to identify a configuration that met these requirements with minimum magnet system cost. Several axicell magnet configurations were considered, and a baseline configuration was chosen.

The configuration of the axicell superconducting magnets (CS1) is shown in Fig. 1. These magnets are 3.8 m in diameter and have 19.8 MA-turns. The peak field at the winding is 10.8 T. The magnets can employ Nb_3Sn conductors cooled by pool boiling or by forced cooled helium at 4.2 K. A NbTi conductor is used in the low field region to reduce the cost. The magnet design discussed in this paper employs the pool-boil cooling approach.

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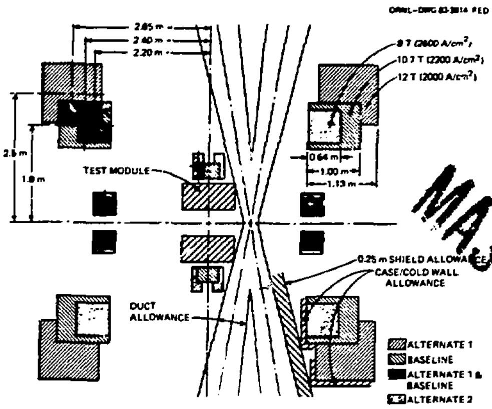

Fig. 1. Composite of base line, alternates 1 & 2 configurations.

Axicell Magnet System Configuration

Requirements and Constraints

The α+T axial field requirements provide 4.5 T at Z = 0 m in the test volume space for generating desired neutron capability and provide 12-T field at Z = ±2 m at the ends of the axicell for ion confinement. The axial field in this region must not be less than 2 T (i.e., the same as the minimum end-plug field). The sizes and locations of the magnets must be compatible with system integration constraints, which include access for neutral beams, access for test modules, and adequate clear bore to accommodate the plasma with halo. Sufficient space must also be provided for magnet neutron shielding. The ripple on the axial field should be no more than 10% for assuming magnetohyrodynamic (MHD) stability of the plasma. The ac power requirement for the axicell should be limited to 10 MW in support of the overall machine objectives. The peak field on the superconducting coils should not be greater than 12 T. If feasible, the field should be reduced to ~8 T to avoid the need for Nb_3Sn superconductors — a less mature technology than NbTi.

Approach and Procedure

The simplest approach to satisfy these functional constraints is a simple mirror. A single pair of coils, each carrying 26.2 MA-turns with a mean radius of 1.4 m and located at Z = ±2 m can meet the field on axis requirements. The peak field at the winding is 15 T. This high field leads to selection of resistive coils. The power required for these magnets is ~200 MW, which is unacceptable.

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A three-coil set was considered that consisted of (1) a single resistive coil at Z = 0 with a radius of 1 m (to fit around the test module) to produce the 4.5 T on axis at Z = 0, and (2) a pair of resistive choke coils at Z = ±2 m (each with a mean radius of 0.32 m). Because these coils have small radii, the field on axis dips down to a minimum of 1.7 T at Z = ±1.2 m, which is not acceptable.

These studies led to magnet configurations with four or five coils. Three alternates (Fig. 1) were studied in detail. It was concluded that four coils are needed as a minimum — a pair of background superconducting coils located far enough on either side of the center of the machine to clear the beam ducts. These coils provide a 4.5-T field on axis at Z = 0. A pair of resistive choke coils at Z = ±2 m augment the background coil field to produce the 12-T choke field. A coil set with these features is designated as Alternate 1 in Fig. 1 (see Table 1). Two variations on the basic four-coil set were considered. Each utilized a resistive coil or coils at Z = 0 in the shadow of the test module to provide a part of the 4.5-T field on axis at Z = 0 (designated Baseline and Alternate 2 in Fig. 1).

Table 1. Coil configuration alternates for D-T axicell

Option	Coil	Mean axial position Z_m (m)	Mean radial position R_m (m)	Axial build ΔZ (m)	Radial build ΔR (m)	Winding current density (A/cm²)	MA-turns
Baseline	CC1	±2.00	0.32	0.34	0.34	2450	2.83
	CS1	±2.40	1.90	1.00	0.90	2200	19.80
	CS0	0.00	1.00	0.40	0.30	1420	1.70
Alternate 1	CC1	±2.00	0.32	0.34	0.34	2450	2.83
	CS1	±2.65	2.50	1.13	1.13	2000	25.53
Alternate 2	CC1	±2.00	0.36	0.42	0.42	2750	4.85
	CS1	±2.20	1.90	0.64	0.64	2600	10.65
	CS0	±0.20	1.10	0.20	0.50	1950	1.95

Comparison of Alternate Configuration

A comparison of the costs of the Baseline and alternates 1 and 2 is provided in Table 2, which illustrates the cost advantage of the resistive coil(s) at Z = 0. Alternate 1, which has no coils in this location, is the most costly. Coils at Z = 0 also reduce the MA-turns required in the background coils from 25.5 MA-turns in Alternate 1 to 19.8 MA-turns in the Baseline or 10.7 MA-turns in Alternate 2. Also, the mean radius of the background coils is reduced from 2.5 to 1.9 m. Both of these effects reduce the capital cost of the superconducting coils — a major system cost driver. A further advantage of introducing coils at Z = 0 is the reduction in peak field in the winding of the superconducting background coils.

Table 2. Cost of axicell configuration alternates

	Baseline	Alternate 1	Alternate 2
Ripple, %	3.5	0	8.5
Peak field in S/C coils, T	10.8	12.0	8.0
AC power, MW	9.5	4.9	19.0
Cost,* $million			
Capital	21.8	44.9	10.1
Operating	7.1	4.8	13.4
Total cost, $million	28.9	49.7	23.5

*Based on 10-year life, 10% duty factor.

Although Alternate 2 is attractive due to the 8-T peak field, the baseline selection was made on the basis of ripple and ac power requirements.

Baseline Configuration

The baseline configuration for the D-T axicell magnet system is shown in Fig. 2, along with other subsystems (e.g., neutral beams, shield, test module, and plasma). It satisfies all plasma and mechanical system integration requirements. The resulting axial field for this region is shown in Fig. 3.

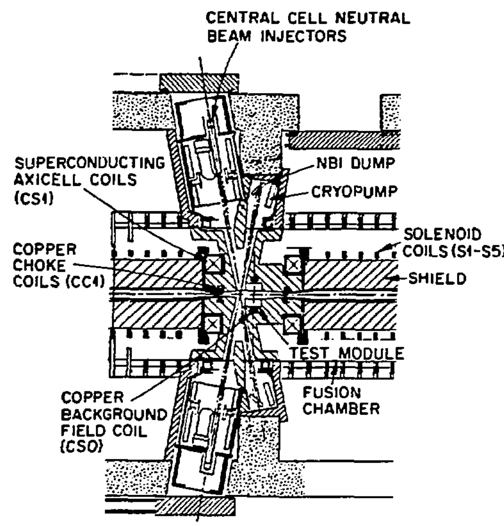

Fig. 2. D-T axicell configuration.

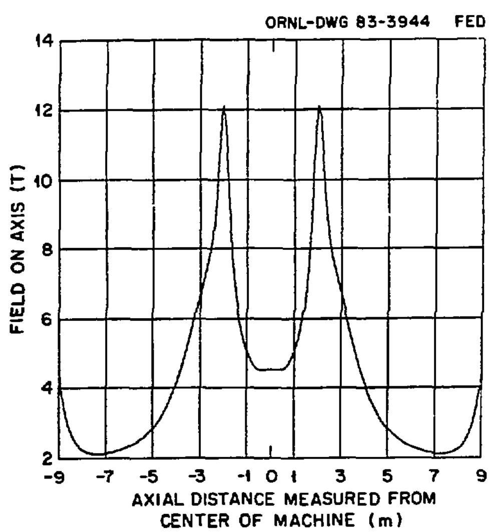

Fig. 3. Axial field profile for central cell region of MFTF-α+T.

D-T Axicell Background Coils Design

The axicell background coils (CS1) are the new coils. They do not exist in the present *MFTF-B* device. The peak field at the winding is 10.8 T (see Table 2). They employ hybrid superconducting winding — a Nb_3Sn conductor in the 8- to 12-T region and a NbTi in the 0- to 8-T region. The winding is bath cooled with 4.2 K helium. The coil windings are designed to operate in the cryostable mode. The conductor design, the winding design, and the performance analysis for these superconducting coils are described in the following subsections.

Choice of Conductor and Operating Current

The Nb_3Sn and NbTi cable conductors are shown in Fig. 4, and their parameters are listed in Table 3. These conductors were originally proposed for 12-T toroidal field (TF) coils [2]. A short length of the Nb_3Sn conductor has been recently manufactured for testing [3]. The conductor with cowound, stainless steel U-channel is ideal for CS1 coils which have high hoop loads in the winding, and can be graded to achieve the overall winding current density of ~2000 A/cm². The conductor is rated for 16.5 kA; its critical current as a function of field and magnet load line is shown in Fig. 5.

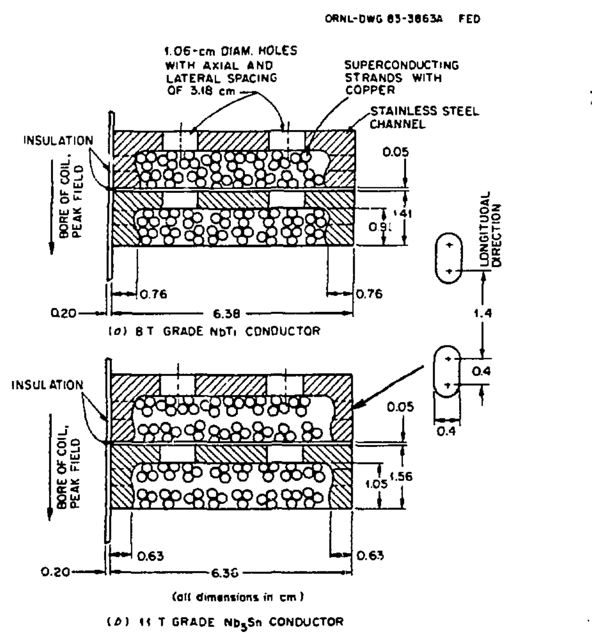

Fig. 4. An 8-T grade NbTi conductor (a) and an 11-T grade Nb_3Sn conductor (b).

Table 3. Major parameters of Nb_3Sn and NbTi conductor for the TF coils.

Description	Nb_3Sn 11-T grade	NbTi 8-T grade
General approach	Pool boiling	
Winding approach	Double pancakes inside casing	
Hybrid Nb_3Sn and NbTi	Nb_3Sn (above 8-T) NbTi (up to 8-T)	
Conductor concept	Cables of triplets of strands in steel channel	
Operating current, A	16,500	
Description of channel		
Width, cm	6.38	
Side thickness, cm	0.63	0.76
Hole diameter, axial and lateral spacing, cm	1.06 3.18	
Plate thickness, cm	0.51	0.43
Overall height, cm	1.56	1.41
Description of cable		
Number of triplets	16	
Number of strands	48	
Strand diameter, cm	0.288	0.268
Helium in channel grove, %	42	
Superconductor area per cable, cm²	0.525	0.329
Copper stabilizer annealed		
RRR	150	
Area per cable, cm²	2.60	2.37
Fully normal heat transfer		
Watts per unoccluded surface, W/cm²	~0.24	

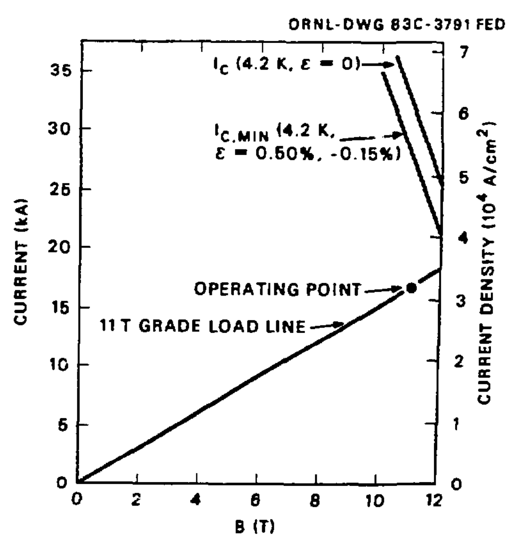

Fig. 5. Operating margin in I_c and T

Winding Layout

The winding layout is shown in Fig. 6, and its main parameters are listed in Table 4. The winding utilizes double pancakes to facilitate grading of the conductor to achieve ~2000 A/cm² winding current density. Each pancake consists of three grades of conductor (11 T, 8 T, and 5 T). The conductor in the high field region has more superconductor/copper and a relatively thick stainless steel channel, whereas the conductor in low field region has less superconductor/copper and a relatively thin stainless steel channel. Grading the conductor in this manner takes advantage of the reduction in the magnetic field and Lorentz force load away from the magnet bore where the field is lowest.

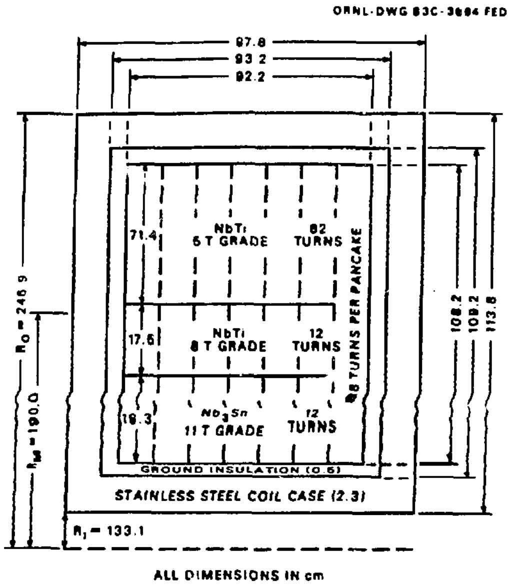

Fig. 6. CS1 coil winding layout.

Table 4. CS1 coil parameters

Electromagnetic	
Ampere-turns	19.8 MA-turns
Peak field	10.8 T
Operating current	16.5 kA
Conductor current density	2050 A/cm^2
Winding current density	1990 A/cm^2
Overall current density (including structure)	1800 A/cm^2
Geometric	
Mean radius	1.90 m
Mean axial position	±2.40 m
Axial width (ΔZ)	0.978 m
Radial width (ΔR)	1.138 m
Number of pancakes	14
Number of turns per pancake	86
Total number of turns	1204
Cryogenic	
Operating temperature	4.2 K
Stability margin	100 mJ/cm^3
Quench	
Stored energy per coil	1170 MJ
Self inductance of each coil	2 x 4.30 H
Maximum temperature rise in the winding	200 K
Minimum area of copper in the conductor	2.37 cm^2
External dump resistors	2 x 0.061 Ω
Time constant with the dump resistors	70 s
Maximum discharge voltage	1.0 kV

The operating current is 16.5 kA, which is ~80% of the critical current at 11 T. Conductors of all grades have the same width but different thicknesses. The winding consists of 14 pancakes, each pancake has 86 turns, and the total number of turns is 1204. The winding provides 19.8 MA-turns (see Table 4). The turn-to-turn insulation has holes to provide bubble percolation, and it is 0.5 mm thick. The pancake-to-pancake insulation is 2 mm thick. Integrated lifetime radiation dose at the insulation is ~10^{10} rad. For this reason, Polyimide is specified as the insulation material. The conductor splices are made by soldering superconducting strands with a lap joint of adequate length (~50 cm) to reduce the joint resistance [4]. The joint is supported by a stainless steel back-plate with some small shimming immediately before and after the joint.

Static Stability and Conductor Performance

The winding is cooled by a pool boiling liquid helium bath at 4.2 K. In the conductor cross section, about 42% of the cable space is occupied by the liquid helium. The superconducting strands are in direct contact with the helium.

One of the requirements is that the conductor/winding must operate in the cryostable mode. This means that the heat flux at the conductor surface must not exceed a critical heat flux value [2,3] of 0.24 W/cm^2 for the conductor. The conductor operating current is selected so that its surface heat flux will not exceed 80% of the critical recovery heat flux.

The peak heat loads in the winding occur in the turns at the inside diameter of the coil using 11-T grade Nb_3Sn conductor. These heat loads are due to nuclear heating, which is maximum in this region including the heat conduction from the coil case through ground insulation. The heat conduction from the coil case to the winding is also due to the nuclear heating loads in case. The peak heat loads in the Nb_3Sn conductor are given in Table 5. The design heat flux is 0.19 W/cm^2. The estimated critical heat flux (0.24 W/cm^2) needs to be verified experimentally [3]. The winding would operate in the cryostable mode, since the design heat flux is less than 80% of critical heat flux; however, detailed dynamic stability analysis is required to confirm this conclusion.

Table 5. Peak heat loads and stability considerations for the winding

Parameter	Winding	Coil case contribution	Total
Peak heat loads in 11 T grade conductor, W/cm			
Nuclear heating	0.013	0.021	0.034
Joule heating in normal zone	6.830		6.830
Total peak heat load	6.843	0.021	6.864
Peak heat flux at the conductor surface, W/cm^2			0.19
Critical recovery heat flux, W/cm^2			0.24

Quench Analysis

The discharge voltage and the hot spot temperature in the winding must be limited to 1000 V and 200 K, respectively. The corresponding discharge characteristics with an external dump resistor are shown in Fig. 7. The resistor is grounded at the midpoint. The peak discharge voltage at the winding is ±1000 V, and peak temperature rise is less than 200 K. This discharge data has been computed using the Thermal

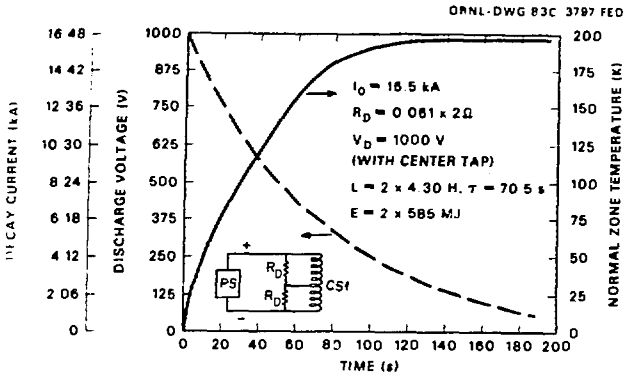

Fig. 7. Quench characteristics of the CS1 coils.

Analysis for Stability and Safety (TASS) code for pool boiling magnets [5].

Winding Pack Stresses

The in-plane and out-of-plane running loads on the CS1 coil are 64.23 and 0.22 MN/m, respectively. The in-plane running loads are equilibrated by hoop stress in the winding and in the case, while out-of-plane loads are equilibrated by bending stress in the case. The hoop and bearing stresses in the conductor are: σ_θ = 47 ksi and σ_{brg} = 0.3 ksi. These are less than the allowable stress of 54 ksi.

To assess design margins, stresses were calculated at critical points throughout the winding and compared with permissible stress (see Table 6). The maximum channel web bending stress due to the Lorentz load appears in the 11-T grade conductor (the effect of ventilation holes on conductor stress is included). The results of stress analyses on the winding pack are summarized in Table 6. All the stresses are within design allowances.

Table 6. Summary of winding pack stresses

Description	Actual stress (ksi)	Allowable stress (ksi)
Interturn insulation compression	35	40
Interpancake insulation compression	0.15	40
Dilational tensile stress		
Channel	36.6	54
Copper	16.6	23
Bending stress in web of channel	38	54
Tresca membrane stress in channel	71.6	75
Tresca membrane-plus-bending stress in channel	73	112.5

Coil Case/Cold Structure Stresses

The out-of-plane axial load on the winding produces a uniform pressure on the 2.3-cm-thick sidewall of the coil case (see Fig. 4), which must be equilibrated in plate bending. The stresses in the sidewall are calculated as a simply supported plate with the maximum out-of-plane load of 0.22 MN/m uniformly distributed, producing a bending stress of 50 ksi that is less than the allowable 54 ksi.

The coils are supported at four axial locations around the periphery of the coil by intercoil supports which carry the resultant axial force. The section of the coil between supports must carry the axial running loads in beam bending. The combined stress in the coil case due to plate bending and beam bending is 51 ksi, which is less than the allowable stress of 54 ksi.

Conclusions

The baseline configuration of the magnets and design of the superconducting CS1 coils for the D-T axicell, satisfies all the requirements for plasma performance and mechanical system integration. However, the normal coil, CS0 (at Z = 0) placed just outside the test module, needs to be removed along with the test module every time access to the test space is required. This may be acceptable. If the CS0 coil poses any problems for the test space access, it is possible to relocate it. Alternatively, it could be eliminated with the use of larger superconducting CS1 coils with peak fields of 12 T, as in Alternate 1.

Acknowledgments

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