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OCTOPOLE DESIGN CONCEPTS FOR THE MIRROR END CELL*

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ABSTRACT

A goal of minimum cost was pursued very strongly by the mirror project team. The team has concluded that a more compact and cost effective end cell magnet system could be achieved by employing octopole magnets. Feasibility of an octopole end cell magnet design was studied as part of FY'84 Fusion Power Demonstration (FPD) work under the direction of Lawrence Livermore National Laboratory (LLNL). This paper describes sizing and design studies of a superconducting octopole magnet.

Magnetic field requirements were supplied by LLNL for the end cell region. Based on these requirements, the Fusion Engineering Design Center (FEDC) synthesized an end cell magnet system. The final end cell magnet system at the conclusion of the FPD study consisted of a 24-T choke coil, a small octopole, a large octopole and a mirror circular coil. Many octopole magnet configurations were studied, but the final large octopole design consisted of four saddle coils. The saddle-shaped coils were preferred over other shapes for ease of fabrication.

This paper describes the scoping design study of the saddle coil winding and its support structure. The support concept for interconnecting the four saddle coils (to form the octopole) is described. An octopole consisting of saddle coils can be fabricated using current conductors and coil winding technology.

INTRODUCTION

Past mirror studies employed an end cell magnet system that consisted of a choke coil, several C coils and a circular coil. Larger size and higher cost were the two unattractive features of these end cell magnet systems.

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During FY'84, LLNL proposed several changes to the machine configuration. Two most significant changes were a central cell employing long magnet modules with a small radial winding build and an end cell consisting of a larger octopole, a smaller octopole, a 24-T choke coil and a mirror coil. This initial configuration is shown in Fig. 1. The long solenoidal modules were considered fabricable using the current superconducting wire and magnet winding technology. Initially, the larger octopole was shown as a one-piece magnet. Fabrication of such a magnet was considered very complex, if not impossible. FEDC proposed that the octopole should be constructed from eight saddle coils. The saddle coils were considered easier to fabricate. LLNL proposed even a simpler octopole design that had only four saddle coils. The four-saddle-coil octopole design was preferred over the eight-saddle-octopole design due to the interface needs of the plasma heating system. However, the eight coil octopole generated only one-half error field in the end region of the saddle coils, as compared to the four octopole design. The latest configuration is shown in Fig. 2. The larger octopole consists of four saddle coils; each saddle coil has stepped-end turns on one side. This feature leads to complex magnet winding and support structure concepts.

Fig. 1. FPD-III magnet configuration.

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Fig. 2. Minimars magnet system.

CONFIGURATION STUDIES

The first iteration of the end cell magnet set is shown in Fig. 3. This magnet set consisted of two octopole coils, a choke coil and a mirror coil. Both octopole coils employed continuously-wound, one-piece windings. The end cell magnet system simultaneously satisfied a number of complex magnetic field requirements for achieving physics goals. These requirements can be best explained by referring to Figs. 4 and 5. Figure 4 requires that the fields at the centerline of the choke coil and mirror coil must be 24 T and 6 T, respectively. The field at the middle of the larger octopole must not exceed 1.5 T. Referring to Fig. 5, the peak field at point M (inside the larger octopole coil at a radius ≈ 1 m) must be at least 0.1 T less than the field at $r = 0$. Additionally,, a field mirror ratio of 2.0 must be provided along the flux line passing through the point of minimum field at $r = 1$ m, discussed above. In Fig. 5, the 2.0 mirror ratio point is marked as "X" near the far end of the larger octopole — a similar location must be found at the near end. Sufficient space must be provided between the point "X" and the winding bundle for accommodating the plasma vessel, nuclear shielding and coil case. The plasma cross-section at the mid-point of the larger octopole must be nearly circular.

Fig. 3. FPD-III end cell magnet set.

Special attention was focused at studying the feasibility of fabricating a continuously-wound, single-piece octopole, as shown in Fig. 6. A single-piece octopole appears attractive for interfacing with plasma heating (ECRH) systems and for providing minimum perturbation in the ideal magnetic field profile desired by physics. On the other hand, a single-piece

Fig. 4. Field profile along the z-axis.

Fig. 5. Field plot in the end cell region.

octopole is considered very difficult and expensive to fabricate. A new three-axis winding machine must be developed that can handle a $4 \times 4 \times 4$ -m coil. This winding machine will be several times more complex than the C coil winders developed by LLNL. Furthermore, the octopole must be removed as a single piece if required by routine maintenance needs.

Fig. 6. A continuously-wound, single-piece octopole.

The whole unit must be replaced if a part of the coil is damaged. Because of these multiplicity of problems, FEDC proposed an octopole design that employed eight identical saddle coils. Each saddle coil can be fabricated with the currently available C coil winders with minor modifications. Individual saddle coils can be replaced should they develop irreparable faults. It may also be possible to remove only a few (1 or 2) saddle coils to gain access to the components inside the octopole bore. Because of these attractive features, the saddle coil octopole design concept was adopted as a baseline.

LLNL performed an extensive design study to identify an octopole design that employed only saddle coils. As a result of this study, the configuration of Fig. 2 emerged. The larger octopole has only four saddle coils. The end cell configuration satisfied all physics needs to the first order.

The new end cell configuration is shown in Fig. 7. The end cell has four sets of coils, i.e., a 24-T choke coil with a peak field of 17 T on a superconducting background coil, a smaller octopole with a peak field of 21 T, a larger octopole with a peak field of 10.2 T and a mirror coil with a peak field of 13.5 T. Peak fields on all superconducting coils, with the exception of the larger octopole, are too high. Further iterations are needed to develop an optimized end cell configuration. Issues associated with designing of the larger octopole with a peak field of 10.2 T are discussed in the following sections.

OCTOPOLE SCOPING DESIGN

An octopole design consisting of four individual saddle coils can satisfy the physics requirements. The designing of this coil is challenging, but attractive winding and support structure concepts are possible. One of the

saddle coils of the larger octopole is shown in Fig. 8. Each saddle coil is 6 m long and 3.2 m wide. End turns on one end are staggered. Each coil carries 6.9 MA turns and experiences a peak field of 10.2 T in the staggered end. A 10-T field contour passing through the top most saddle layer is shown in Fig. 9. Major parameters of the saddle coils are shown in Table 1.

Fig. 7. End cell configuration.

Fig. 8. Saddle coil with staggered end turns.

Fig. 9. Field distribution in the staggered end turns region of the octopole.

Table 1. Octopole Design Parameters		
Parameter	Unit	Value
Ampere turns	MA-turn	6.9
Peak field at winding	T	10.2
Winding current density	A/cm ²	3000
Winding cross-section	m × m	0.5 × 0.5
Stored energy	MJ	700
Length of mean turn	m	10
Nuclear heating in winding	mW/cm ³	1
Peak radiation dose	rads	10 ¹⁰
Coil weight	kg	40,000

Each saddle coil consists of three sub-saddle coils. Each sub-saddle consists of 100 turns of Nb₃Sn, cable-in-conduit, forced-flow conductor. The conductor carries 18 kA under normal operating conditions. Five turns are cooled in series. The helium mass flow through each cooled circuit is 4 g/s. Helium enters at 4.2 K, 15 atm and exits at 5.5 K, 13.7 atm. The following discussion describes the analysis that supports the selected coil design concept.

Recent Tokamak Fusion Core Experiment (TFCX) studies¹ developed reasonable winding current densities that can be achieved at various field levels. Figure 10 shows winding current density achievable with a Nb₃Sn cable-in-conduit, forced-flow conductor. The peak winding temperature must be less than 5 K. The critical conductor current is also shown for a Nb₃Sn cable-in-conduit conductor with an Incoloy conduit.²

Fig. 10. Nb₃Sn cable-in-conduit, forced-flow conductor.

A Nb₃Sn conductor with an Incoloy conduit is selected for the saddle coils. The Nb₃Sn conductors lose their current-carrying capability as a function of mechanical strain. The strain may be caused by several factors, such as coil winding operation, differential contraction factors of conduit and conductor, and conductor dialation following coil energization. For a most compact design, the total conductor strain at normal operating current must be reduced to zero, if possible. The winding strain can be eliminated if the conductor is reacted (i.e., heated up to 700°C) after the coil is wound. This requirement creates several design and fabrication challenges,² but they can be met. The Nb₃Sn conductor and Incoloy have similar coefficients of contraction and therefore cooldown compressive strain is negligible in such a conductor design. However, the coil must withstand the dialational strain. The dialational strain in the saddle coil is on the order of 0.002.

A Nb₃Sn conductor with an Incoloy conduit has a critical current of 34 kA at a peak field of 10.2 T and temperature of 4.2 K (see Fig. 10). The critical current is reduced to 32.5 kA, as 0.002 dialational strain is imposed on the conductor when the coil is energized. The saddle coils are expected to experience significant amounts of nuclear heating load, which must be removed by liquid helium flowing through the conductor. If exit temperature of helium is assumed as 5.5 K, the current-carrying capability of the conductor is further degraded. The critical current of the conductor at 5.5 K becomes 23 kA. The operating coil current is usually limited to ~ 80% of the critical current. Thus, the saddle coil conductor current is 18 kA. This results in a winding current density of 3300 A/cm² if structural design of the saddle coils is considered similar to the TFCX TF coil design, discussed in Ref. 2. The number of turns in each saddle coil is 300. Each saddle coil consists of three unequal sub-saddles. Each sub-saddle has 100 turns which can be arranged as 20 wide and five deep.

A maximum of five turns can be cooled in series if incident peak nuclear heating at the conductors facing the plasma is 1 mW/cm³. Successive series-cooled five turns are assumed to receive less nuclear heat load than the preceding turn. However, each turn is assumed to experience uniform heat load along its whole perimeter. Liquid helium enters the cooled circuit at 4.2 K and 15 atm and exits at 5.5 K and 13.7 atm. The amount of helium flowing through each circuit is 4 g/s. A schematic of winding cross-section and helium-cooling connections is shown in Fig. 11. The helium manifolding can be placed in the stepped-end turns of the saddle coil.

Fig. 11. Conductor and helium cooling arrangement for a single sub-saddle winding pack.

Each saddle coil assembly will be encased in a 5-cm-thick coil case. The overall structural assembly of a saddle coil is shown in Fig. 12. This structural design concept is discussed in Ref. 3.

Fig. 12. Complete octopole saddle coil with structure.

CONCLUSIONS

An octopole design consisting of four individual saddle coils can satisfy the physics requirements. The new end cell magnet design is challenging, but an attractive winding and structural design concept is feasible. More detailed studies will be made for this octopole configuration as part of the future Minimars studies.

REFERENCES

1. "TFCX (Tokamak Fusion Core Experiment) Preconceptual Design Specification," Rev. 2, Princeton Plasma Physics Laboratory, June 15, 1984.
2. S. S. Kalsi, "TFCX Current Density and Nuclear Heating Limitations for Superconducting Tokamaks," to be presented at Sixth Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, March 3-7, 1985.
3. J. A. O'Toole and D. C. Lousteau, "Evolution of the Fusion Power Demonstration Tandem Mirror Reactor Configuration," to be presented at the Sixth Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, March 3-7, 1985.

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