A LARGE SUPERCONDUCTING MAGNET FOR FUSION RESEARCH*

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Abstract

Fusion technology will require superconducting fields of moderately larger working volume and of moderately higher field strength (by several orders of magnitude) than previously designed. A novel design of a toroidal magnet that accommodates the large forces generated by such a magnet, was previously reported.[3] This paper describes modifications to the coil shape required when the toroidal magnet is comprised of discrete coils as well as a segment of a toroidal system that is being constructed and, when tested, will verify the reported prescription. The coil segment has a bore approximately 1.0 m x 1.3 m and will be tested for a maximum field of 100,000 G.

Introduction

Recent favorable developments in plasma physics have caused renewed and increased activity in the field of fusion reactor technology. The power density of a fusion reactor increases as B^4, and the cost of the magnet increases at a somewhat lower rate (somewhere between B and B^2).[1,2] Because of these relationships, it is generally agreed that fusion reactor designers intend to take advantage of the highest fields available. Commercially obtainable superconductors are already capable of producing magnets with fields in excess of 150,000 G in relatively small bores, a field level that taxes the known limits of structural design. In addition to high fields, fusion reactors will require larger working volumes (by several orders of magnitude) than any previously designed. The combination of high-field and large working volume requires superconducting magnets well beyond present technology.

A novel design of a toroidal magnet, which partially accommodates the large forces generated by a high field, large volume magnet, was previously described.[3] In a toroidal magnet, the field strength within the useful volume varies inversely with the radius from the axis of symmetry, and in almost all cases the conductors generating such fields will be subject to bending moments in addition to effective internal pressure. It was shown[3] that a conductor tethered at either end will be stable if it is in pure tension and, therefore, not subject to any bending moments. The net forces are then taken on a cylindrical structural element to which the conductor is tangent. Figure 1 shows this curve, which, except where the conductor lies flat against the cylindrical support, is a solution of the equation:

$$r\,(d_2r/dz^2) = \pm 1/k\,[1 + (dr/dz)^2]^{3/2} \quad . \qquad (1)$$

The curve generated by equation (1) describes the conductor shape when there are no gaps in the winding--continuously wound toroidal windings.

This paper presents the required modification to the conductor curve when the torus is comprised of a discrete number of coils. Further, a segment of a toroidal system now being designed to test and verify engineering details of the reported prescription is presented.

Torus of Discrete Number of Coils

Equation (1) is the correct expression for the shape of a conductor lying in a toroidal field which in its useful volume varies inversely with the radius from the axis of the torus. In order to have the 1/r field distribution in the useful volume, the torus must be continuously wound, i.e., there must be only small gaps or none at all between coils, so that the effect of gaps between windings is negligible. A practical coil system must necessarily be made up of a number of discrete coil segments for access to the useful volume, as well as for ease of manufacture. We now explore the modifications required in such a system.

Boris and Kuckes[4] have derived closed analytical expressions for the vector potential and the magnetic field generated by a discrete number of axisymmetric multipole line currents in a system similar to that shown in Fig. 2. For a system composed of n coils, at $\theta = 0$, Boris and Kuckes indicate that the expression for B_θ is:

$$B_\theta = 1/kr \left\{ 1 - \frac{[(r_1/r)^{2n} - (r_1/r)^n]}{[1 - 2\,(r_1/r)^n + (r_1/r)^{2n}]} - \frac{[(r/r_2)^{2n} - (r/r_2)^n]}{[1 - 2\,(r/r_2)^n + (r/r_2)^{2n}]} \right\} . \qquad (2)$$

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As n approaches infinity, the expression reduces to $B_\theta = 1/kr$, the expression from which equation (1) was derived.

Modifying equation (1) by equation (2), we find that the shape of a constant tension conductor will be the curve generated by the solution of:

$$r\,(d_2r/dz^2) = \pm 1/k\,[1 + (dr/dz)^2]^{3/2} \left\{ 1 - \frac{[(r_1/r)^{2n} - (r_1/r)^n]}{[1 - 2\,(r_1/r)^n + (r_1/r)^{2n}]} - \frac{[(r/r_2)^{2n} - (r/r_2)^n]}{[1 - 2\,(r/r_2)^n + (r/r_2)^{2n}]} \right\}. \qquad (3)$$

Numerical solution of equations (1) and (3) by computer codes generates the curves shown in Fig. 3 for systems of infinite n as well as $n = 40$ and 25, for which r_1 and r_2 are the same. Comparison of these curves indicates that as $n \rightarrow 0$, the curves become more circular, and the point of tangency, z_1, is slightly closer to the r axis. With fewer coil segments, all other parameters remaining the same, less superconductor will be used. The prescription of equation (3) with $n = 25$ was used to design the coil section described below.

Description of a Proposed Coil Segment

General Description

Fusion reactors of the size presently envisioned, i.e., 2000 MWe, 160,000 G fields, generated by toroidal magnets of major and minor radii of about 10 m and 6 m respectively,[5] have brought about almost unanimous consensus that such magnets will be constructed with superconductors.[6] Design and construction of superconducting magnets of this size and field level are well beyond the capabilities of present technology. Therefore, on July 1, 1972, the Plasma Physics Laboratory undertook the first step of what may eventually become a ten-year developmental program whose aim is to produce a reactor size toroidal coil segment capable of safe, reliable operation at fields of 160,000 G or more. This first step, a two and one-half year developmental program, is to design, fabricate, and test to 100,000 G at the inside conductor, a pure tension coil. The coil will be one segment of a torus comprised of twenty-five equally spaced coils of dimensions $r_1 = 50$ cm, and $r_2 = 150$ cm. To produce this field, 25×10^6 ampere turns are required; therefore, the proposed single coil segment will be capable of producing 10^6 ampere turns, one twenty-fifth of the total required.

The Coil

The coil segment, whose dimensions are shown in Fig. 4, is composed of twelve pancakes of one-half cm wide Nb_3Sn copper-stabilized conductor. It has a bore of 1.0 x 1.31 m at the inside conductor. Figure 5 shows the cross section of the coil giving dimensions, pancakes, lines of constant radial field, B_r, and lines of constant field, B_θ.

The conductor is designed to carry 220 A at 4° K while subjected to any combination of the B_r and B_θ fields shown in Fig. 5. To accommodate those fields and to minimize expended funds, varying thicknesses of copper are used for stability, and varying thicknesses of stainless steel are used for strength. The three pancakes nearest each edge are made of three types of materials, and the innermost six pancakes, of two types as shown in Fig. 5. Table I lists the three materials used in the two types of pancakes and gives the current density in that section of the pancake.

TABLE I

Material	Total Thickness cm	Copper Thickness cm	Superconductor Thickness and other cm	Average current density in section A/cm^2
1	0.051	0.028	.005	8630
2	0.036	0.013	.005	12200
3	0.028	0.013	.005	15700

The average current density over the bundle area of 125 cm^2 (9.6 x 13.0 cm, see Fig. 5) is 8000 A/cm^2. Because of the high friction between adjacent conductors in the coil, the constant tensile force across the bundle is the average of the tension due to the maximum and the minimum axial fields, B_θ, across the coil. In the case at hand, the average tension in each strand is 75 lb; the maximum stress in the strap is 53,000 psi; and the maximum elongation is 0.18%, assuming no prestressing of the superconductor.

Each of the twenty-five coil segments will produce a centering force of 370,000 lb at a maximum field of 100,000 G at the inner conductor, a force which must be simulated in a test stand.

The Test

Since only one of the twenty-five modules is being constructed, a test stand must be designed, so that everywhere in the vicinity of the test coil the magnetic field will have the same magnitude and direction as if the coil segment were located in the torus. Many simulating configurations are possible, and several, using both water-cooled copper and NbTi superconducting auxiliary coils, have been investigated. One possible solution using normal water-cooled copper coils, which are available at the Plasma Physics Laboratory, is illustrated in Fig. 6. These coils require 9.2 MW of dc power to produce 100,000 G at the inside conductor of the test coil, and the properly shaped field inside the bore of the test coil. Should this test stand be adopted, available submarine batteries will be utilized to energize the system. Other configurations of test stands are being investigated, and ultimately the decision will be made on economic considerations, i.e., the cost of energizing auxiliary coils that are on hand with existing but un-bussed batteries vs the cost of new NbTi auxiliary coils and their peripheral equipment, such as Dewars and power supplies.

The design of the Dewar that surrounds the test coil segment will depend, to a great extent, on the configuration of the test stand. The Dewar, however, must be capable of transmitting the high centering forces through low conductivity supports installed in the superinsulation. A Dewar similar in construction to those described previously[6] is being designed.

Conclusion

The coil described in this paper represents the largest bore, 100,000 G magnet thus far known to have been considered for construction. For the first time it will provide us with the capability of testing a pure tension, moment-free configuration. These important first steps are necessary to solve the many unanswered questions and provide solutions to problems in the design of high-field, large-bore superconducting magnets to be used in fusion reactors.

Acknowledgement

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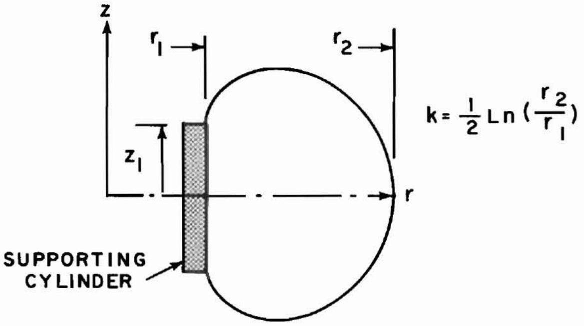

Fig. 1. Mathematical Shape of a Constant Tension, Current Carrying Element When the Field Is Inversely Proportional to r in the Useful Volume.

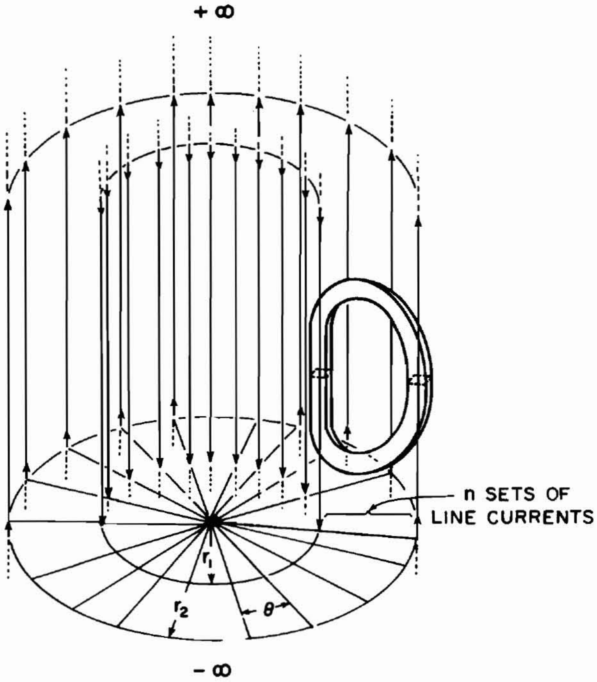

Fig. 2. A Toroidal Configuration of n Line Currents.

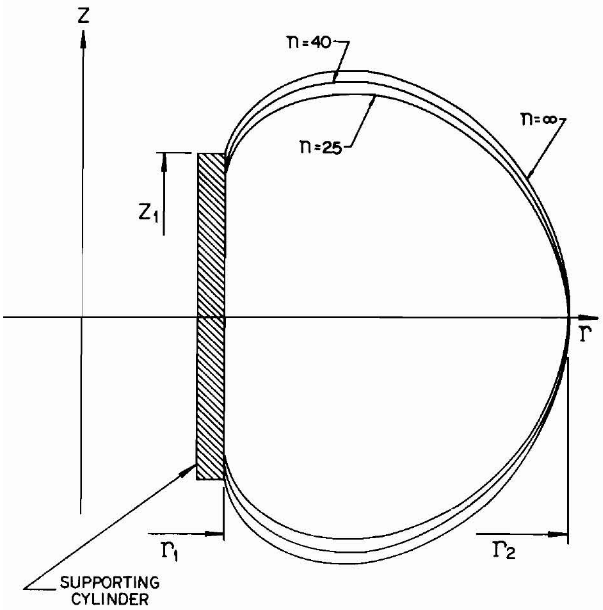

Fig. 3. Mathematical Shape of Constant Tension Current Carrying Elements in Fields Generated by n Discrete Coils.

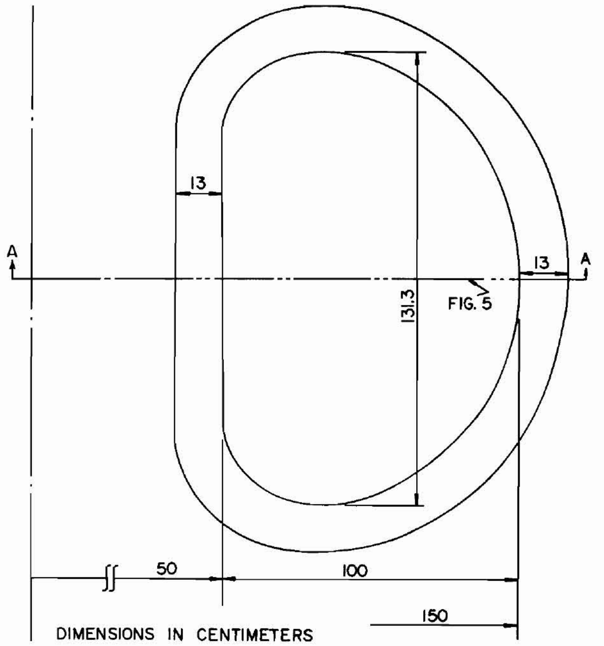

Fig. 4. Dimensions of the Proposed Coil, One of 25 Segments.

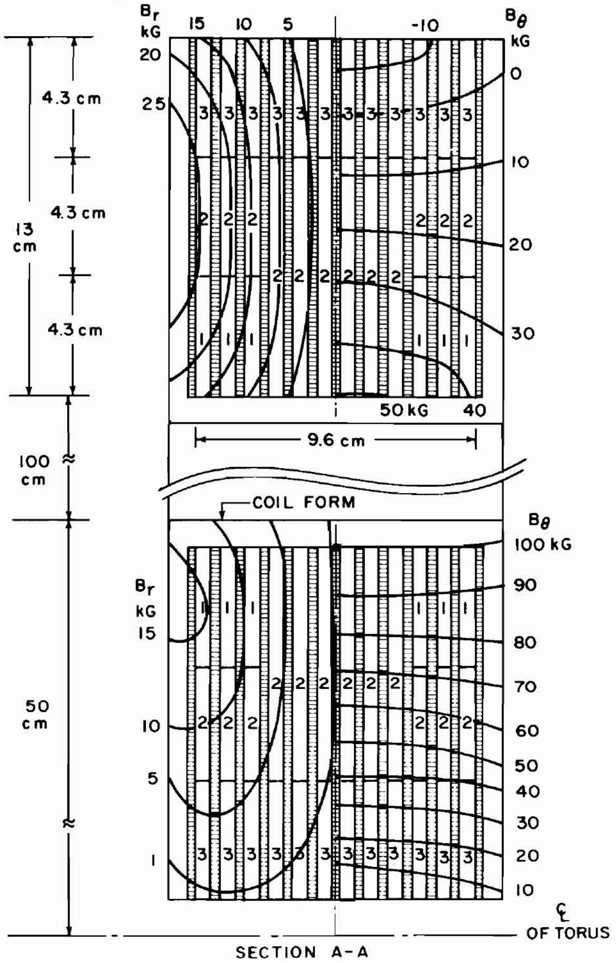

Fig. 5. Cross Section of the Proposed Coil.

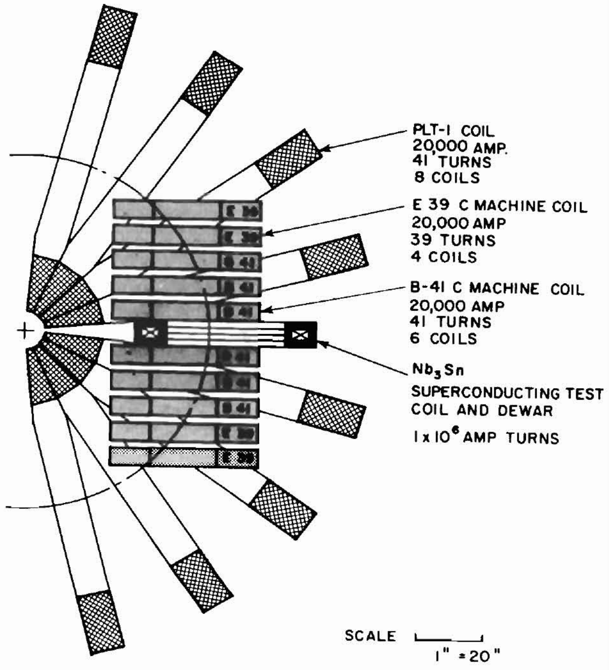

Fig. 6. A Satisfactory Test Stand Configuration Composed of Eight PLT-1 Coils, Ten C-Machine Coils and One Nb_3Sn Test Coil.