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MAGNET DESIGN FOR A FUSION ENGINEERING RESEARCH FACILITY

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Abstract

The conductor layout for the magnet for a device to generate a plasma of thermonuclear parameters is described. Shielding and access considerations place restrictions on the layout not normally encountered in experimental magnets. The coil cross-section is made to vary along the current path in order to reduce conductor surface induction to tolerable levels for Nb-Ti and Nb_3Sn superconductor. The final result is a coil with a minimum-B field shape which permits adequate access for plasma refueling by neutral particle injection.

Introduction

A research facility has been proposed to duplicate the plasma conditions of density and temperature which are expected to be encountered in a fusion reactor.[1] This machine will be a net consumer of power with neutral particle injection at high energy and current resupplying material and energy. The purpose of the device is to provide the reactor environment of particle and energy flux for testing of materials and subassemblies.

The tailoring of coils to provide the magnetic field for such a device is the subject of this paper. Since the fusion environment places rather stringent demands on shielding for the magnet coils, the problems of field shaping are more like those which will be encountered in fusion reactor design than those which arise in designing coils for contemporary plasma physics experiments.

Design Requirements & Considerations

The basic requirement is for a minimum-B mirror field throughout a plasma volume with a 25 cm radius circular cross section at the midplane. The desired value of the axial mirror ratio is 2.0.

Two values of central induction were considered, corresponding to two different levels of superconductor technology. The first, or "low-field" magnet would be fabricated from niobium-titanium superconductor, using present day technology. The central induction would be 3.75 Tesla. Maximum bulk current density would be no greater than 5.0k Amp-cm^{-2}, and the maximum induction in the conductor would be $\sim$ 9.0 Tesla.

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The second, or "high-field" magnet would be of essentially the same geometry as the low-field magnet, but anticipates advances in the technology of utilizing Nb_3Sn superconductor. Thus, the maximum conductor induction woul be $\sim$ 12.0 Tesla, with a proportionate increase in central induction to 5.0 Tesla. Bulk current density would remain limited to $\leq$ 5.0k Amp-cm^{-2}. Nb_3Sn conductor would be used only in high-field zones with Nb-Ti making up the major part of the winding cross section.

It became apparent, early in the design process, that a "Yin-yang" minimum-B coil configuration was preferred to a "baseball" coil because of the large amount of space required for neutral-beam injection equipment. The Yin-yang coil typically produces a field with a radial well which is shallow as compared with a baseball field and one in which mod-B contours are closed only for B values slightly greater than the minimum.

Coil Development

In analyzing a Yin-yang field using the computer code, MAFCO[2], it is most convenient to describe each current filament as a set of eight connected arcs, as shown in Figure 1. The current elements can be completely described in terms of X_0 and Z_0, the center of one of the large arcs lying in the -z half-space, A, the radius of one such arc, and Ψ, the half-angle subtended by the arc. In what follows, A will be referred to as the major radius and X_0 as the minor radius.

Initital consideration of shielding and access requirements showed that a coil having approximately the shape shown in Figure 2 would be needed. Figure 2 is a section through the y = 0 plane. In this plane appear the two regions in which fields at conductor surfaces are most critical. The sweep angle, Ψ, of the coil was limited to 70° in order to accommodate the injection beam paths. The corner of the coil was cut off for the same reason.

The first attempt to lower the turnaround induction was made by thickening the turnaround section. This can be done most simply (for computational and not constructional purposes) by allowing Ψ to increase with increasing X_0 for successive layers of current elements. While this method has been successful in the conceptual design of another coil,[3] it failed in the FERF design. Owing largely to the fact that Ψ_{max} is still limited to 70° because of access requirements, the thickening requires layers of small X_0 to be swept through angles of only $\sim 57°$. This in turn raises the central field, lowering the mirror ratio. The mirror ratio may be increased, at the cost of coil efficiency, by separating the two halves (making all Z_0 negative), but, at a separation which gives a mirror ratio of 2.0, the minimum-B character of the induction is destroyed.

An alternate, more direct method of reducing the turnaround induction was sought. Lengthening (rather than thickening) the section at the turnaround will have a nearly first-order effect on the surface induction since the effective sheet current in that region is inversely proportional to the section length. Since the length at the crossover section is already determined, the length must be changed as the coil sweeps through the angle Ψ on the major radius, and through 90° on the minor radius.

For a given current filament whose crossover coordinates are $z_c = Z_0 - A$, $x_c = X_0$, the turnaround coordinates are:

$$z_t = A\cos\Psi - Z_0 - X_0\sin\Psi \text{ , and}$$

$$x_t = A\sin\Psi + X_0\cos\Psi$$

as shown in Figure 3. Then, in order to stretch the turnaround section, the desired section is laid out, and Z_0, A, and Ψ for each filament are determined from z_c, x_c, z_t, x_t.

This procedure gives $\Psi < 70°$ for most of the filaments. But in this case, very low values of Ψ ($\sim 60°$) are necessary only for the outermost (large A) filaments. There is, therefore, but little decrease in the mirror ratio as compared to the decrease caused by attempts to thicken the coil. It was found that small adjustments in mirror ratio were best made by adjusting the average major radius, A, for given cross sections rather than by moving the coils apart.

After many iterations, a ratio of the section length at turnaround to that at crossover of ~ 1.33 gave nearly the required reduction in surface induction. In the various stages of design, the current density was reduced below the value of 5k A-cm^{-2} originally allowed for, so surface inductions slightly greater than 9.0 and 12.0 Tesla may be tolerable. Absolute upper limits of 9.0 and 12.0 Tesla, respectively can be obtained by further stretching of the cross sections by a few percent. One advantage of the small ratio of plasma volume to total field volume is that small changes in coil details have little effect on the field near the center.

The coil design as it now stands is shown in Figure 4. Practical considerations for winding the coil may require methods of achieving the desired cross sections which are different from those employed in generating the current elements for computer analysis. Here again, the effect of these differences on the field within the plasma volume is expected to be small. The coil parameters are:

	Low Field	High Field
B ($z = 0$)	3.75 Tesla	5.00 Tesla
B_{max} (axial)	7.62 Tesla	10.15 Tesla
R	2.03	2.03
B_{max} at conductor:		
Crossover	9.20 Tesla	12.27 Tesla
Turnaround	9.61 Tesla	12.81 Tesla
Current density:		
Region I	1.73 kA-cm^{-2}	2.31 kA-cm^{-2}
Region II	3.47 kA-cm^{-2}	4.62 kA-cm^{-2}

The distance between mirror points on the z-axis is 500 cm.

The radial well depth over a plasma radius of 25 cm is ~ 1.007. Computations which are now in progress will determine whether such a shallow radial well can stably confine a plasma of $\beta = 0.5$.

The forces on the magnet were calculated by mocking-up one quarter of one coil with a single filament located at the current-averaged centroid. Sections of this filament were deleted in calculating $\vec{B}$ at the center of each missing section. The force per unit length, $\vec{I} \times \vec{B}$, was then calculated for each section.

The results are shown in Figure 5. The total forces, provision for which must be made in the mechanical design, are large. The force tending to push the two coils together is $\sim 52.8 \times 10^6$ Newtons. The force tending to flatten each coil into an annular disc is $\sim 530.1 \times 10^6$ Newtons. The force tending to straighten each coil out lengthwise is $\sim 195.7 \times 10^6$ Newtons.

References

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2. Perkins, W. A. and Brown, J. C., MAFCO--A Magnetic Field Code for Handling General Current Elements in Three Dimensions, UCRL-7744-Rev. II, LLL, November 9, 1966.

3. Moir, R. W. and Taylor, C. E., Magnets for Open-Ended Fusion Reactors, UCRL-74326, LLL, November 15, 1972.

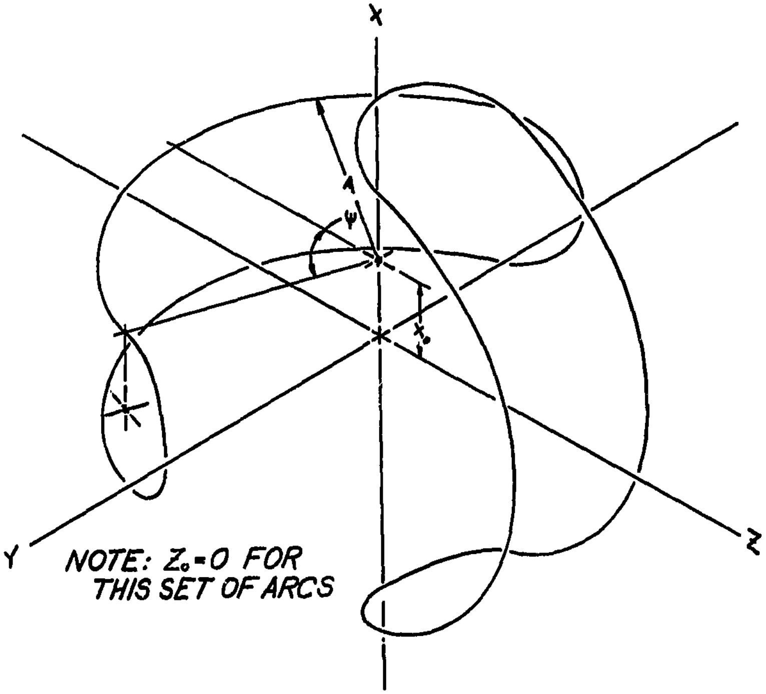

Figure 1. Parameters for Describing Yin-yang Current Elements

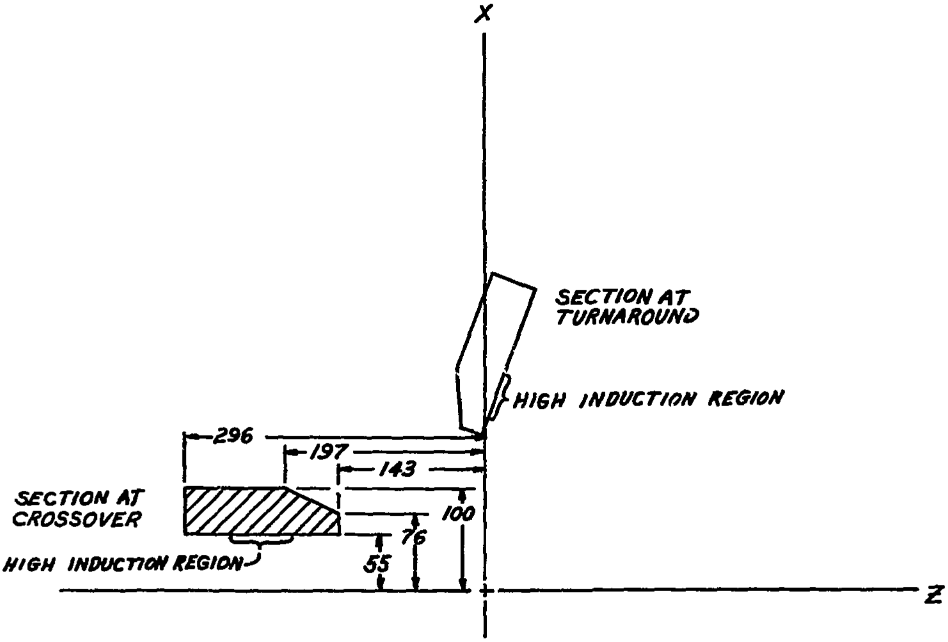

Figure 2. Initial FERF Coil Layout

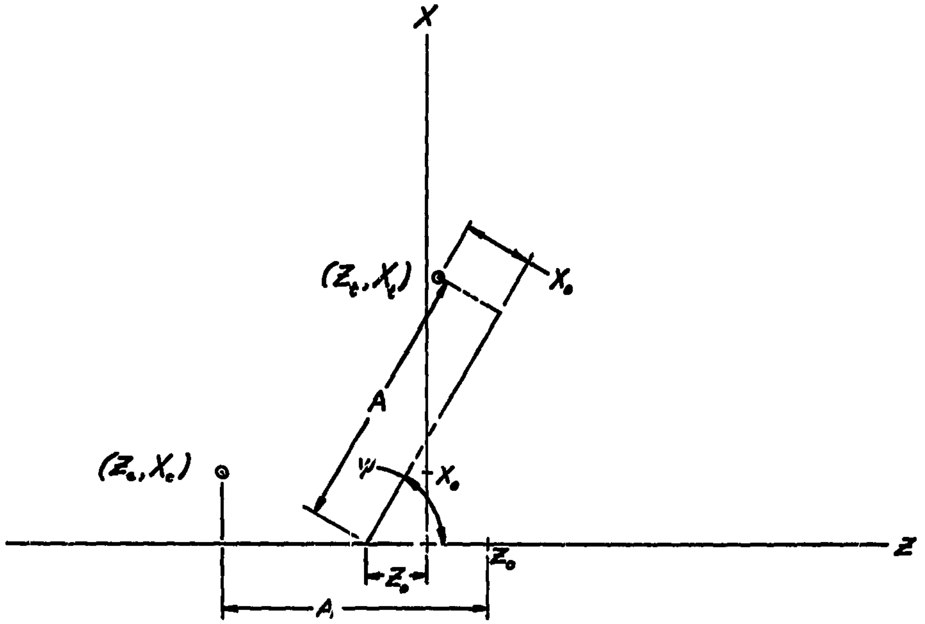

Figure 3. Transformation of Point from Crossover Section to Turnaround Section

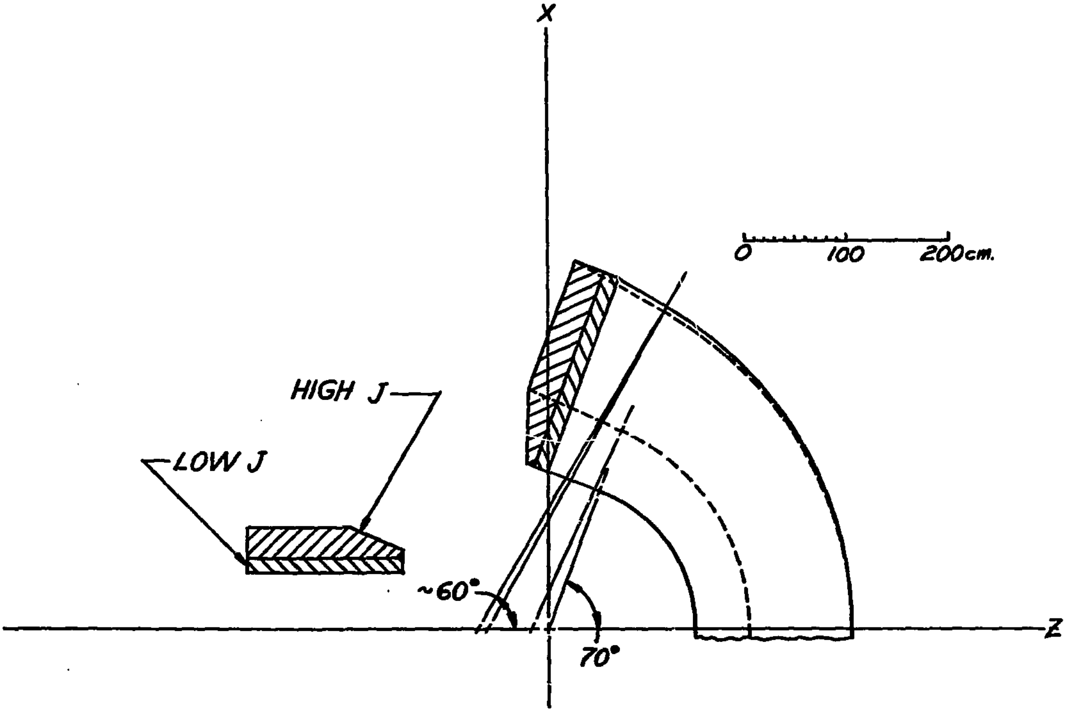

Figure 4. Final FERF Coil Layout

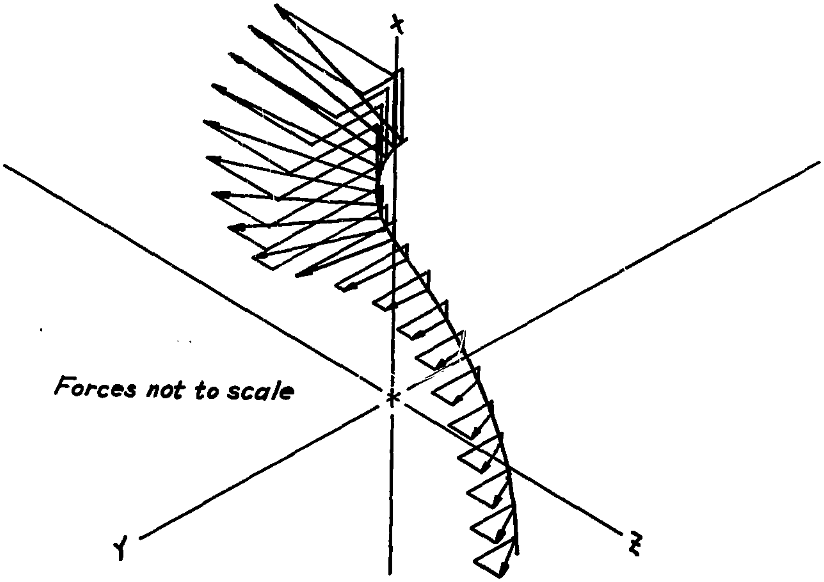

Figure 5. Force Distribution on $\frac{1}{4}$ of One Coil for Low-field Magnet