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TITLE: A STELLARATOR HELICAL VACUUM VESSEL

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A STELLARATOR HELICAL VACUUM VESSEL*

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Abstract

A design study of a stainless steel, heavy wall, helically shaped vacuum torus has been made for use in a proposed Stellarator configuration. The study concerns itself with the shape of the vacuum vessel and the division of the vessel into components that can be machined and welded together into a helical configuration. A complication in the design requires that a circular magnet coil be located at the minor toroidal axis and that this coil be embedded within the periphery of the vacuum vessel. The vacuum vessel has a minor toroidal axis diameter of 4 meters, a 68.6-cm shell diameter, and a 1.9-cm wall thickness. It twists about the minor toroidal axis twice in 360°. (An n value of 2).

It is proposed that the unit be made of cylindrical segments with the ends of the cylinders cut at appropriate lengths and angles to form the helix. A mathematical derivation of the dimensions necessary to produce the required shapes of the segments has been made. Also, drawings of the vacuum vessel components have been produced on LANL's CTR CAD/CAM system. The procedure developed can be used for any value of n as dictated by physics requirements.

Introduction

The vacuum chamber contemplated for a proposed Stellarator system is a toroidal tube, circular in cross-section, which spirals around a 4 meter diameter planar circle. The chamber will be made of 304 stainless steel, is 27 inches in outside diameter with a 3/4 inch thick wall. The outer circumference of the chamber will have a groove approximately 6 inches by 6 inches formed into the vacuum chamber to accommodate a hard core magnetic coil. In cross-section the groove is positioned on the circumference and extends inward toward the vacuum chamber center. The construction is such that the center line of the hard core coil forms a basic planar circle, the hard core coil spirals around this planar circle and the vacuum chamber spirals around the hard core coil. Figure 1 is an illustration of the proposed Stellarator system and shows the vacuum vessel as it will appear in the final configuration. Figure 2 shows the vacuum vessel setup for the hard core magnetic coil assembly.

The number of turns around the planar circle (designated n) will be specified by the technical requirements of the program. For purposes of this study n was assumed to be equal to 2 but can be any number with the same analysis applicable.

Section Derivation

To achieve reasonable costs the unit will be fabricated of sections probably made of forgings which will be welded together to form the chamber. The form of each section will be a cylinder of proper diameter and thickness with the hard core groove an integral part of the section. To obtain the final shape of each section it will be necessary only to machine flat the two ends of the cylinder at the proper angles and to take a finish cut through the hard core spiral groove.

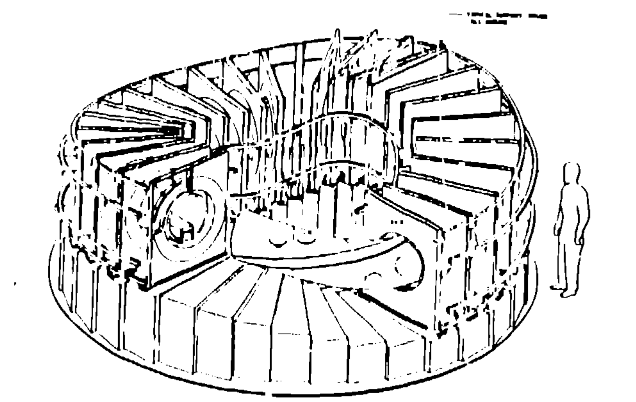

Fig. 1. Proposed Stellarator System.

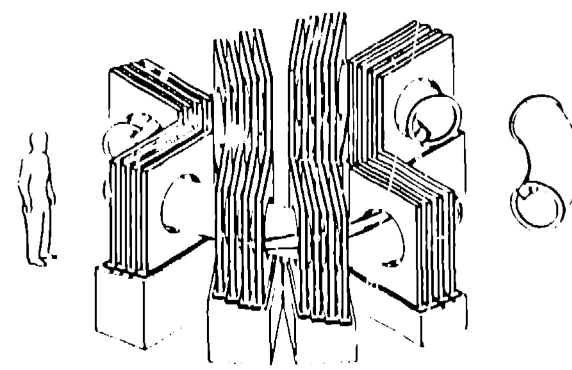

Fig. 2. Configuration For Hard Core Assembly.

It is expected that 32 TF coils will be required around the chamber. Thus one can divide the chamber into 32 sections placed such that the TF coils cover the weld joints of the sections. This leaves base metal for the penetrations required for vacuum ports, diagnostics and antenna openings. With 32 sections the maximum deviation of the circular portion of the chamber from the true helix shape of the unit is on the order of 1%.

A 90° model of the combination vacuum chamber-hard core coil was made. It is shown in Fig. 3. Each circular plate represents a vertical plane of the vacuum chamber surface and is in proper orientation with the hard core coil.

Early in the program studies were made with 6° vertical plane segments with an attempt to define each section to have circular ends corresponding to Fig. 3. In order to have circular ends, the cross section of the segment would be slightly elliptical. It became apparent that the two ends of the segment required a different size ellipse which varied approximately 1/4

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Fig. 3. Vacuum chamber Model.

of an inch in the major diameters. The segments also varied from segment to segment. These variations could be accomplished in chamber tooling but present serious complications which would make the tooling very expensive.

Since sections made up of cylindrical pieces would be the least difficult to manufacture, a study was undertaken to determine the feasibility of their use for fabrication of the chamber. The key to the success of this approach is to exactly define the center lines of adjacent segments of the vacuum chamber. The angle formed by these lines is then bisected by a plane perpendicular to the plane of the two center lines. Cylinders with these lines as axes will intersect the plane in ellipses that match perfectly. This condition is ideal for the chamber requirements. If one can define the center-lines and the hard core-lines within each segment then the parameters necessary for manufacture of the segments can be resolved.

To define these lines reference is made to the model shown in Fig. 3. Since 32 segments form a good condition for the chamber, as noted above, the model can be set up with its vertical planes at 11.25 degree increments. A coordinate system can be established which defines the coordinate positions of the ends of the center-lines and the hard-core lines. Use of Fig. 4 and Fig. 5 illustrates the determination of these coordinate points. A description of the method used to find the space coordinates of the center-line and hard-core intersection with the vertical planes follows.

In Fig. 4, Point A represents the zero points of the coordinate axis of the system. This point is the center of the hard-core coil with the center-line of the vacuum chamber directly below. The hard-core coordinates at the zero point are (0,0,0). The center-line coordinates are (0,0,-2.375) (1/4 scale) In

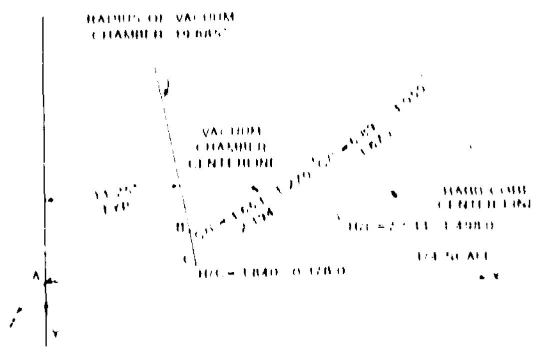

Fig. 4. Vertical Plane Coordinate System.

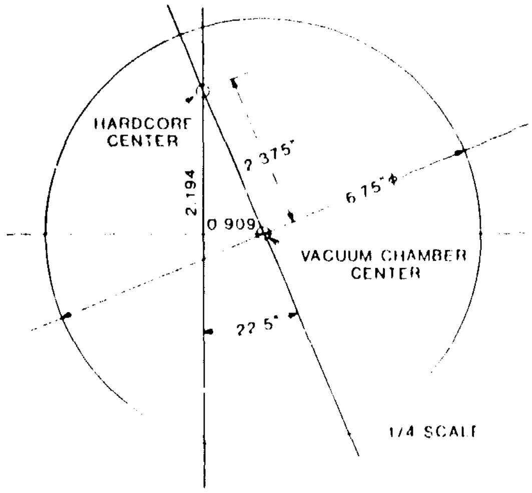

Fig. 5. Vertical Plane at 11.25°.

Fig. 4, Point B is the center-line intersection with the vertical plane at 11.25° and Point C is the intersection of the hard-core line with the 11.25° vertical plane. Figure 5 is typical of that used to determine distances to be integrated into the coordinate system of the hard-core and center-line intersection points. At 11.25° Point B has the coordinates 3.663,-1.270, -2.194 and Point C has the coordinates 3.840,-.378,0. In like manner the hard-core and center-line coordinates can be found around the entire chamber. It should be noted that for n = 2 one half of the chamber is identical to the other so that only 16 sections need to be defined. Figure 6 is a CAD/CAM representation of all 32 vertical planes which shows all the center-lines and hard-core lines of the Stellarator system. Once the coordinates are established for the center-line and hard-core intersection points each segment can be characterized. To illustrate the method the section between 11.25° and 22.5° will be analyzed.

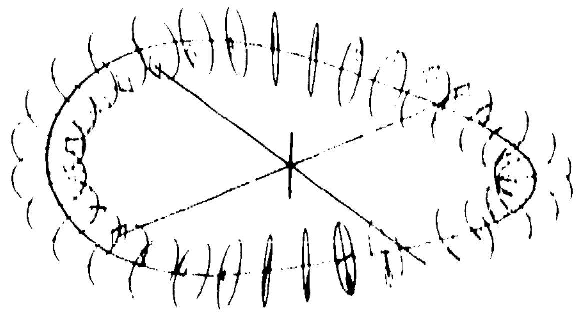

Fig. 6. Vertical Plane CAD/CAM Representation.

The steps are as follows:

1) To find the equation of the bisect plane at 11.25° and also the angle that the center line makes with this plane it is necessary to use the defined center lines extending from zero to 11.25° and 11.25° to 22.5°. One of the center lines must be extended in space until it equals in length the other center line. The ends of these lines then become a perpendicular bisector of the bisect plane. This fact coupled with another defined point on the plane (the intersection of two center lines) allows the determination of the bisect plane equation. It is:

$$3.515X - 1.563Y + .359Z - 14.073 = 0$$

The angle that the center line makes with this plane becomes 5.52^{o}. using the same procedure, at 22.5^{o} the bisect plane equation is:

$$3.076X - 1.972Y + .661Z - 26.102 = 0$$

and the angle of the center line with the 22.5^{o} bisect plane is 4.32^{o}. These angles are the cutting angles on the cylinder to form this section. The length of the center line from 11.25 to 22.5^{o} is 14.888 inches.

2) The angle of rotation between the planes at 11.25^{o} and 22.5^{o} is found by a determination of the planes passing through adjacent center lines at 11.25^{o} and 22.5^{o}. The angle between the perpendicular bisectors of these planes (these bisector lines are the minor axes of the ellipses formed at each bisect plane) becomes the angle of rotation of the bisect planes relative to each other in each section. The plane equations are at 11.25^{o},

$$X + 3.924Y + 7.294Z + 17.32 = 0$$

and at 22.5^{o}

$$X + 3.513Y + 5.875Z + 13.69 = 0$$

The angle between the perpendiculars to these planes is 5.07^{o}.

3) To find the angle of rotation that the start of the helix makes with the minor axis of the bisect plane it is necessary to find the equation of the plane made up of coordinates of the hard core line projected onto the bisect plane together with the center line coordinates and the equation of the minor axis line. The offset angle between the plane and line is then determined and becomes 6.64^{o}. The axial distance between the minor axis and hard core projection can be determined from analysis of the triangle formed by the hard core projection coordinates and the two center line coordinates and is found to be .116".

The helix angle is simply the angle formed by the lines made up of the hard core projection coordinates and perpendiculars from these coordinates to the section center line. For this section the angle is 23.28^{o}.

The hard core groove length is the length of the line between the hard core projection coordinates and is 15.42".

CAD/CAM Characterization

A complete CAD/CAM analysis of the sections from 0 to 90^{o} was made. Figure 7 shows the bisect planes superimposed on the vertical planes between 0 - 90^{o}. Figure 8 is the section from 11.25-22.5^{o} from which all parameters necessary for machining this section were obtained. Table I lists the dimensions for each section.

Acknowledgements

[1] Roger Smith, Don Willerton, Pat Witt, Brad Wright.

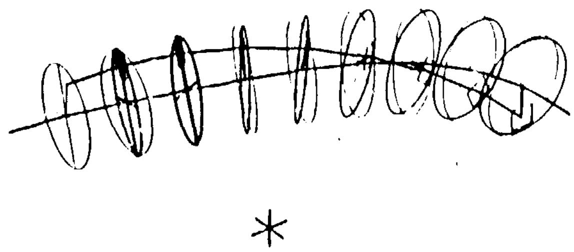

Fig. 7. 0-90^{o} Vertical and Bisect Plane Comparison.

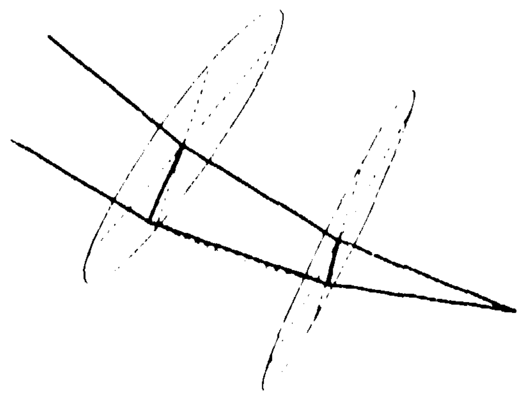

Fig. 8. 11.25^{o} to 22.5^{o} CAD/CAM Section.

TABLE I

CAD/CAM VACUUM CHAMBER SECTION PARAMETERS

Section (Degrees)	Bisect Plane Major Axis Angle With Center Line First Plane	Second Plane	Minor Axis Rotation Angle	Bisect Plane Center Line Length	Projected Hard Core Line Length	Rotation Minor Axis to Hard Core First Plane	Rotation Angle Of Helix	Axial Start Point of Helix Relative to Minor Axis
0-11.25	96.468	84.469	5.167	15.524	15.418	23.729	22.262	.443
11.25-22.5	95.531	85.651	3.074	14.887	15.434	6.635	23.281	.106
22.5-33.75	94.349	86.868	5.105	14.401	15.443	13.572	24.136	.170
33.75-45.0	93.132	92.578	22.552	14.139	15.449	42.813	24.635	.353
45.0-56.25	87.482	93.132	22.552	14.139	15.549	90.0	24.635	.417
56.25-67.5	86.868	94.349	5.105	14.401	15.443	42.831	24.136	.353
67.5-78.75	85.651	95.531	3.074	14.887	15.434	13.572	23.244	.170
78.5-90.0	84.469	96.468	5.167	15.524	15.418	6.619	22.297	.088