THE TOROIDAL FIELD COILS
FOR THE PRINCETON DIVERTOR
EXPERIMENT

BY

J. C. CITROLO

AND

C. W. BUSHNELL

PLASMA PHYSICS
LABORATORY

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Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $ *___; Microfiche $1.45

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Princeton University
Plasma Physics Laboratory
Princeton, New Jersey

The Toroidal Field Coils for the
Princeton Divertor Experiment

by

J. C. Citrolo, C. W. Bushnell

April, 1975

This paper was presented at the "Fifth International Conference on Magnet Technology" at Frascati, Italy April, 1975, and has been accepted for publication in the proceedings of the conference.
The Toroidal Field Coils
for the Princeton Divertor Experiment

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ABSTRACT

The PDX device, scheduled for completion in January 1977, will be used to determine the effectiveness of Poloidal Divertors in controlling the impurities of CTR plasmas. The twenty coils of the Toroidal Field Coil System have an elongated bore 3.65m high and 1.88m wide. They will produce a field of 25 kG at a machine radius of 1.4m. The total stored energy of Toroidal Field will be 150MJ.

The Toroidal Field Coils are topographically interlocked with the Divertor Coils and will be demountable to provide easy access to the divertor. This aspect of the coils is a major consideration in the design of both the coils and the supporting structure. In this paper, the coils, the joints in the coils and the procedure for their disassembly are described. The various ways in which the structure supports the coils against the magnetic forces and the resulting coil stresses are discussed. The procedure for the coil fabrication is also presented.
The Toroidal Field Coils
For The Princeton Divertor Experiment

J.C. Citrolo, C. W. Bushnell

SUMMARY

The toroidal field coils for the Princeton Divertor Experiment (PDX) and their supporting structure are described. The special demountable nature of the coils and the problems which result from this feature are discussed. The procedures for assembly and fabrication of the coils are presented.

INTRODUCTION

The PDX is scheduled for completion in January of 1977 and will be used to determine the effectiveness of Poloidal Divertors in controlling the impurities of CTR research plasmas. The subject of this paper, the toroidal field coils of this machine, produce the main confining field for the plasma and are topologically interlocked with the many poloidal coils which are necessary in the establishment of the divertor field. Since repeated rearrangement and replacement of the divertor coils is contemplated, it has been decided to make the toroidal field coils demountable to provide access to these coils. This aspect of the coils is a major consideration in the design of both the coils and the supporting structure.

Figure 1 shows a general arrangement of the PDX device. Twenty coils comprising the toroidal field coil system are grouped around a central column. The coils are mounted between upper and lower shelves which are attached to an outer torque frame. In the bore of the toroidal field coils are the coils used for ohmic heating the plasma and the vacuum chamber which contains the divertor coils.

The magnetic forces on the toroidal field coils arise from the interaction of the current in the coils with two different magnetic
fields: the self field produced by the toroidal coils and the fields from the poloidal coils. The interaction of the coil current with the self field causes an inward force on the inner leg of the coil and an outward force on the outer leg of the coil. Due to the nature of the toroidal field, which is higher at the inner radius, the force on the inner leg is higher than the force on the outer leg. The net difference is termed the centering force. The centering force on this coil is 1.84 x 10^6 lbs.

The interaction of the coil current with the non-coincident components of the various poloidal fields causes lateral or out of plane forces at the top and bottom portions of the coils. The forces at the top of each coil are opposite in direction to the forces at the bottom and the effect is to produce an overturning moment on the coil which tends to rotate the coil about its horizontal axis.

The forces on the inner legs of the coils are resisted by the mutual support the coils give each other thru their tapered inner legs. The outer legs of the coils are supported by the strongbacks and two large rings which surround the machine. The lateral forces on the coils are supported by the machine structure. The means of coil support will be further discussed as the coil and principal structural components are described.

1. DESCRIPTION

The general machine parameters as they apply to the toroidal field coils are presented in Table 1. Figure 3 shows the principal components of the coil assembly.
Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Major machine radius</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Coil Dimensions</td>
<td>Figure 2</td>
</tr>
<tr>
<td>Field at major radius</td>
<td>25 KG</td>
</tr>
<tr>
<td>Field at inner leg of coil</td>
<td>63.75 KG</td>
</tr>
<tr>
<td>Field at outer leg of coil</td>
<td>14.41 KG</td>
</tr>
<tr>
<td>Total NI</td>
<td>$17.5 \times 10^6$ ampere turns</td>
</tr>
<tr>
<td>Number of coils</td>
<td>20</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>20</td>
</tr>
<tr>
<td>Current per turn</td>
<td>43,700 ampoures</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.190 henry</td>
</tr>
<tr>
<td>Inductive energy</td>
<td>182 megajoules</td>
</tr>
<tr>
<td>Resistance</td>
<td>39.59 milliohm</td>
</tr>
<tr>
<td>Joule heating</td>
<td>2.38 Megajoules</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>2 min.</td>
</tr>
<tr>
<td>ESW time</td>
<td>2.5 secs.</td>
</tr>
<tr>
<td>Net wt. of copper</td>
<td>154,000 lbs.</td>
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</table>

1.1. Toroidal Field Coils

There will be twenty coils, each coil having twenty turns of copper conductor arranged in two layers of ten turns each. The conductor of the inner layers is 3-3/8 inches x 1 inch and the outer layer is 4-3/8 inches x 1 inch. The silver bearing copper will be drawn with a central elliptical hole for a cooling water passage. Each turn will be insulated with .044 inches of "B" stage crossply material over .007 inches of mylar. The insulation will be press cured to a dimension of .042 inches.

To permit disassembly with the vacuum chamber in place, there will be two joints near the top and bottom of each turn of the coil. Figure 4 is a model of this joint. The joint contains an integral key which
is designed to transmit the stresses in the coil across the joint. The joint is held closed by a coil clamp.

Except that an inner turn is cemented to an outer turn for handling convenience, the half pieces of the turns are loose separate pieces and are held together as a coil only by external mechanical clamping. When the coil is disassembled each piece is removed individually. The turn to turn transition will be accomplished by a joggle in the outer leg. Current will flow first through the turns of the inner layer and then to the turns of the outer layer before proceeding to the next coil.

1.2. Coil Joint and Clamp

The clamp serves two purposes. The first is to hold the joints closed, providing good electrical contact and mechanical alignment. Second, it connects the coil to the shelves and transmits the lateral loads on the coils to the shelves.

The clamp housing is a three sided box which fits around the turns of the coil. The fourth side of the box is a pivoted Inconel forging which transmits the clamping force to the joint area. Figure 5 is a photograph of a model of the clamp. A wedge fits between the pivoted forging and the housing and is driven by jacking screws. The clamping force, twenty-five thousand pounds, is one and one half times the lateral load.

The clamp housing is mounted to the upper and lower shelves with a special "tee" slot and key which hold the housing rigid to transmit the lateral loads, yet can be loosened to permit radial adjustment of coil position and lateral movement as required for disassembly.

1.3. Center Column

The center column has a large thrust assembly mounted on each end. See Figure 6. These thrust assemblies provide rigid reactions to the coil forces at critical points on the top and bottom of the coils. The action of these supports is to relieve the bending moments in the coil
joint area enabling the joint to transmit only pure tensile stress. The reaction on each coil from the thrust assemblies is 260,000 lbs. and requires the center column to transmit a vertical force of 5.2 million lbs. from the upper to lower thrust assemblies.

The center column assembly consists of an outer sleeve, one inch thick, and the center column core. The sleeve supports and aligns the upper shelf during assembly. It is also used to anchor the keys between the coils and as a reference for alignment of the TF coils. The bore of the sleeve is 24 inches in diameter and is large enough for a man to enter when the center column core is removed. Holes in the wall of the sleeve permit viewing of the nose of coil to ensure correct alignment.

1.4. Keys

Between each coil and its neighbor there is a tapered stainless steel key. The key covers the side face of the inner leg of each coil. The main purpose of the key is to provide the necessary space for removal of the turns of the TF coils. The key also prevents lateral shearing motion between the inner and outer turns of the coil and gives lateral support to the coil. The lateral loads on the inner legs of the coil are modest but the turns, less than an inch thick, are very flexible in this direction and require support.

The keys are made in four sections and contain three expansion joints. This is to permit the key to "ride" with the coil as the coil experiences thermal expansion. Each key will be tailor made to go with each coil. After each coil is fabricated the thickness of the assembly will be measured in a fixture and the thickness of the key will be adjusted to allow for the build up of tolerances on the turns of the inner leg.
1.5. **Strongbacks and Rings**

The outer legs of the coils are supported by a partial coil case termed the strongback. The coil case is in turn supported by two large rings which surround the machine. The strongback is made of 1/2 inch thick stainless steel and forms a box around the outer turns. Without the strongback, the bending stresses in the outer leg between the ring supports would exceed the yield stress in the copper. The strongback is also used as a fixture to support the coil during disassembly.

1.6. **Torque Frame**

Support against the overturning moment, which is due to the interaction of the TF coil current with the non-coincident components of the poloidal fields is provided through the coil clamps, the shelves and the torque frame. The total effect of all the coils is to produce a horizontal torque of 11.6 million in lbs. on the upper and lower shelves. These torques are opposite in direction and will support each other through the action of the cross braces of the torque frame. These braces are made from eight inch diameter stainless steel pipe.

2. **PROCEDURE FOR DISASSEMBLY OF THE TOROIDAL FIELD COILS**

The procedure described will assume the machine is completely assembled with the vacuum chamber in place. This procedure will be used during the erection of the machine to permit installation of the vacuum chamber after the power tests are finished. The power tests will be made to proof the toroidal field (TF) coils before completion of the machine.

First, the midplane band around the TF coil inner legs is removed. Then the TF coils are pulled back 3/4 of an inch. The keys between the coils remain in place.

The thrust assemblies and the core of the center column are removed.
The upper shelf is now supported by the center column sleeve. This is not as important in the disassembly as it is during coil assembly where the sleeve is used to align the upper shelf to the lower shelf.

Next the upper shelf and the torque frame are removed. The keys, which are actually spacers between adjacent coils, are loosened from the center column sleeve. Access is provided through the 24 inch bore of the sleeve. The keys are then removed and also the center column sleeve.

The TF coils are now moved circumferentially around the machine to take up the spaces left by the keys. The resulting spaces are arranged as shown in Figure 7. The coils stand alone and are supported by these strongbacks.

The coil clamps on a coil adjacent to a space are removed. One side of the coil strongback is removed and the turns of this coil are now accessible. Temporary clamps hold the coil to the strongbacks.

Each half turn of the coil is now removed separately. The outer leg is simply removed outward. The inner leg is moved into the space provided by the removal of the keys. The nose of the inner leg actually traverses the whole coil bundle and into the space on the opposite side. The turn is then removed vertically. Every turn of the TF coil system, four hundred in all, must be removed individually.

3. COIL FABRICATION PROCEDURE

The coils will be fabricated outside the laboratory by qualified vendors. Negotiations are now in progress to select one or more vendors to perform the following tasks.

1. Supply the basic conductor. The conductor will be extruded and drawn, in two sizes, with an elliptical cooling passage. Tests have been performed to show that this is feasible and can be achieved with acceptable tolerances.
2. Rough forming of the conductor. The large radius on each conductor will be made by stretch forming. In this process the bends are made while the conductor is held with a very high tension. Tests have also been made to prove the feasibility of this step.

3. Conductor machining. The proper tapers will be machined on each leg. The cooling passage will be plugged at each end and passages machined to provide access to the cooling hole.

4. Offset bending. Each conductor of the inner leg will be bent to provide the proper radial to parallel transition, which its position in the coil requires. The outer turns will be bent to form the turn to turn transitions.

5. Insulation. Mylar and "B" stage insulation will be applied to the individual turn pieces and to the two-turn assemblies. The "B" stage insulation will be mold cured to establish the dimensional relationship of each piece. Electrical tests of turn to turn and ground insulation will be performed.

6. Final machining. Each two turn assembly will be finish machined to form the joints.

7. Assembly and measuring. The conductors will be fitted and assembled to form 20 turn coils in a special fixture. The coil will be checked and measured for the proper key thickness.

4. CONCLUSION

The demountable feature of the TF coils has complicated the design of both the coil and its supporting structure. The machine is now in the detail design stages. Tests have been performed to check the fabrication procedures and many aspects of the design. Various joint designs have been mechanically tested to check stress and fatigue behavior but the full scale tests with operating current have not yet been made.
This work was supported by the U. S. Energy Research and Development Administration (formerly AEC) Contract E(11-1)-3073.
REFERENCES

Fig. 1. General Arrangement of PDX Device.
O.D.T.F. COIL INSTALLED
192.444 Ref.
96.222

MACHINE

C T.F. COIL

14.014

33.062 R

36.687 R

77.80

36.703

66.124 Ref.

8.084

55.118

88.180*

33.020

* INDICATED DIMENSIONS TO BARE COPPER

Fig. 2. T.F. COIL LAYOUT
20-COIL, 20 TURNS/COIL
Fig. 3. Toroidal Field (TF) Coil Assembly.
Fig. 4. Model of Joint in Toroidal Field (TF) Coil.
Fig. 5. Model of Joint Clamp.
Fig. 6. PDX Elevation View.
Fig. 7. TF Coil Arrangement for Coil Removal