**ELECTROMECHANICAL ANALYSIS OF A PROTOTYPE 20 TESLA,
SINGLE TURN TOROIDAL FIELD COIL FOR IGNITEX**

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Presented at the
13th Symposium on Fusion Engineering
Knoxville, TN
October 2-6, 1989

Publication No. PN-159
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ELECTROMECHANICAL ANALYSIS OF A PROTOTYPE 20 TESLA, SINGLE TURN TOROIDAL FIELD COIL FOR IGNITEX

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Abstract: The fusion ignition experiment (IGNITEX) device is a single turn coil tokamak designed to produce and control an ignited plasma using ohmic heating alone. The proposed high strength toroidal field (TF) magnet operates at a magnetic field on-axis of 20 T, using homopolar generators (HPGs).

In this paper, the electromechanical analysis of a scaled down prototype (0.06 scale in linear dimensions) of the IGNITEX TF magnet is presented. The objective of the Ignition Technology Demonstration (ITD) program is to design, build, and test the operation of a single turn, 20 T, TF coil, powered by an existing HPG power supply system. Unlike conventional TF coils that use multiple turns of the conductor, the single turn coil eliminates the need for turn-to-turn insulation; therefore, better utilizing the available area for stress and thermal management. Precooling of the coil to liquid-nitrogen temperature permits the magnet to operate in a wider temperature regime without exceeding material properties.

Scaling relationships presented in this paper show that temperatures and stresses of a scaled-down coil and their relative distribution will approximate predicted levels of the full-scale IGNITEX device. A finite element program (TEXCOR) which solves a set of coupled electrical circuit, magnetic diffusion, and thermal diffusion equations with temperature dependent properties was developed. TEXCOR provides temperatures and magnetic body force densities for stress analysis of the magnet structure. The effect of flatness tolerance stackups in the TF coil assembly is discussed and methods to characterize and minimize the negative effect of nonideal conditions are given. Generator fault scenarios are also addressed. The analysis results presented in this paper show the feasibility of a single turn, 20 T, TF magnet powered by HPGs. This work is sponsored by the Texas Advanced Technology Program and the Texas Atomic Energy Research Foundation.

Introduction

The production of a controlled thermonuclear fusion reaction represents a major scientific and technical challenge which has eluded mankind for the last four decades. The challenge is nevertheless worthwhile since fusion represents a virtually inexhaustible energy source. IGNITEX has been conceived at The University of Texas at Austin by Marshall N. Rosenbluth, William F. Weldon, and Herbert H. Woodson [1].

The IGNITEX concept is a single turn tokamak designed to produce and control an ignited plasma with ohmic heating alone. Detailed plasma physics analysis indicates the IGNITEX provides an ample ignition margin and a passive means of controlling the ignited phase of the experiment [2]. A critical element to the success of IGNITEX is the on-axis toroidal magnetic field of 20 T. The ITD, powered by Balcones HPGs at the Center for Electromechanics at The University of Texas at Austin (CEM-UT), is intended to confirm the ability of the proposed technology to generate and maintain the high toroidal magnetic field. The TF magnet is exposed to severe magnetic and thermal loading due to high magnetic field and long confinement time. An optimum single turn TF coil design is possible as a result of the development of a sophisticated finite element program (TEXCOR) which predicts magnetic loading and temperature distribution within the magnet structure.

Electromechanical Model

The behavior of a transient, nonlinear, thermally coupled electromagnetic, and uncoupled, quasistatic, linear thermoelastic

system can be described by three sets of partial differential equations; magnetic diffusion equation, thermal diffusion equation, and linear thermoelastic equations. Magnetic diffusion equations can be derived from Maxwell's equations subject to the following assumptions:

1. The magnetic field is quasistationary at power frequency such that displacement currents may be neglected
2. No ferromagnetic material exists

With the above assumptions, one obtains a magnetic diffusion equation as:

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times \left(\frac{\rho}{\mu_0} \nabla \times \vec{B} \right) = 0 \quad (1)$$

where

$\vec{B}$ = magnetic induction or flux density
 μ_0 = permeability of free space
 ρ = resistivity, which is temperature dependent

From Fourier's law and energy balance, the thermal diffusion equation is:

$$\nabla \cdot (k \nabla T) + S = C_p \frac{\partial T}{\partial t} \quad (2)$$

$S = \rho \vec{J}$

where

T = temperature
 C_p = temperature dependent specific heat
 S = heat source
 k = temperature dependent thermal conductivity
 J = current density

The nonlinear thermal diffusion equation and the magnetic diffusion equation are coupled through the material's temperature dependent properties and the heat source due to ohmic heating. The sets of equations governing quasistatic, linear thermoelastic behavior consists of three equations: equilibrium equation, constitutive equation, and kinematic equation. By quasistatic, meaning that the inertial effect is neglected, but the response is still time-dependent. The governing equations are:

1. Equilibrium equation

$$\nabla \cdot \vec{\sigma} + \vec{F} = 0 \quad (3)$$

$\vec{F} = \vec{J} \times \vec{B}$

2. Constitutive equation

$$\vec{\sigma} = \vec{C} (\vec{\epsilon} - \alpha \vec{T}) \quad (4)$$

3. Kinematic equation

$$\vec{\epsilon} = \frac{1}{2} (\nabla \vec{U} + \nabla^T \vec{U}) \quad (5)$$

where

$\vec{\sigma}$ = stress tensor
 $\vec{\epsilon}$ = strain tensor
 $\vec{C}$ = tensor of elastic moduli
 α = temperature dependent thermal expansion coefficient
 $\vec{F}$ = body force density
 $\vec{U}$ = displacement vector

The purpose of the following discussion is to explore the appropriate scaling parameters to scale down a full model into a smaller model in which the magnetic, thermal, and stress fields are an image of fields in the full-scale model. The scaling process is simply a coordinate transformation. We denote $(\bar{x}, t)$ and $(\bar{x}', t')$ as coordinates associated with the full-scale and prototype models respectively. If geometric scale f and time scale g are chosen, then the transformation may be expressed by the following relations:

$$\begin{aligned}\bar{X}' &= f\bar{X}, \quad t' = gt \\ \nabla_{\bar{x}}(\cdot) &= f\nabla_{\bar{x}'}(\cdot), \quad \frac{\partial(\cdot)}{\partial t} = g\frac{\partial(\cdot)}{\partial t'} \\ \bar{J} &= f\bar{J}', \quad \bar{U} = \frac{1}{f}\bar{U}'\end{aligned}\quad (6)$$

Substituting (6) into (1), the transformed magnetic diffusion equation becomes:

$$g\frac{\partial \bar{B}'}{\partial t'} + f^2 \nabla_{\bar{x}'} \times \left(\frac{\rho}{\mu_0} \nabla_{\bar{x}'} \times \bar{B}' \right) = 0 \quad (7)$$

where

$\bar{B}'$ = magnetic induction in terms of $\bar{X}'$ coordinates and time t'

To make $\bar{B}'$ an image of $\bar{B}$, the scaling factors f and g have to satisfy the following relation:

$$g = f^2 \quad (8)$$

To assure the relation above is appropriate, the rest of transformed equations need to be checked. It can be easily verified that the same relation holds. A conclusion can be made that as long as the time scaling factor is the square of the geometric scaling factor, the shape of current pulse is the same, and the current amplitude is linear proportional to the geometric scaling factor, the temperatures, stresses, and the magnetic fields in the scaling model will be an image of full-scale model.

In the application to the toroidal magnet, only the azimuthal component of magnetic field exists due to axisymmetry. Furthermore, the TF magnet is powered by the HPG which can be modeled as a capacitor with the capacitance in terms of the moment of inertia of the rotor and excitation flux. Each sector can be represented as the equivalent R-L-C circuit with equation as:

$$\frac{d(LI)}{dt} + RI + C_e \int Idt = 0 \quad (9)$$

with initial HPG voltage and zero current

where

- L = total inductance which is time dependent
- R = total resistance which is time dependent
- C_e = HPG equivalent capacitance
- I = circuit current

Since the governing equations of the system are nonlinear and coupled, the analytic solution is formidable. A finite element method is used to solve the equations. While isoparametric quadratic elements are used in the space discretization, the backward difference scheme in conjunction with iteration is used in time-march solution. The electromechanic analysis consists of two steps. First, the circuit equation: the magnetic and thermal diffusion equations are solved to obtain temperature and magnetic body force density. Second, a stress analysis of the model subject to the body force density and the thermal loading obtained from electromagnetic analysis is performed by using a 3-D finite element model (ABAQUS [3]).

TF Magnet Electromechanical Analysis

A magnet scale of 0.06 has been selected for the ITD simply due to the linear relationship between geometric scaling factor and the current required to achieve an on-axis 20-T field in a single turn TF magnet. The Balcones HPG power supply is rated at 60 MJ

and 9 MA at 100 V; therefore, the geometric scaling factor of 9 MA/150 MA or 0.06 was selected and the scaled current pulse width for 0.06 scale magnet becomes 36 ms (0.06^2 of 10 s). Selection of the magnet conductor was based on trade-offs between electrical conductivity, yield strength, material stability and plate thickness [4]. Beryllium copper (C17510) was chosen as the conductor material for the prototype TF coil. As produced by Brush Wellman, Inc., Brush Alloy #3 exhibits a room temperature electrical conductivity of 64% IACS and a 0.2% yield strength of 108 ksi. Electrical conductivity of Brush Alloy #3 improves by a factor of 2.3 at liquid nitrogen temperature [5]. The 0.06 scale TF magnet located in the CEM-UT HPG pit (fig. 1) is made by stacking wedge-shaped, BeCu plates with a "bucking cylinder" placed in the central hole of magnet assembly. Precooling the coil to liquid nitrogen temperature permits the magnet to operate for a longer period without exceeding the material capability or degrading material properties. A longer current pulse than that scaled for 0.06 scale magnet shown in figure 2 is obtained from electromagnetic analysis. The elongated current pulse is primarily due to the inductance mismatch between the magnet and the existing power supply system; the 60 MJ HPG system was designed to drive high inductance loads. As a result, much more energy is deposited in the prototype after peak current.

ITD Magnet Operating Parameters

- PEAK CURRENT IN TOROIDAL COIL -- 9 MA
- PEAK TOROIDAL FIELD ----- 20 Tesla
- MAJOR RADIUS OF TORUS ----- 9 cm

4501.0037.1

Figure 1. ITD as located in the CEM-UT 60 MJ HPG pit

Parametric Study

Several analysis iterations were performed to determine several critical parameters of the magnet such as the size and material of the bucking cylinder, the magnitude and distribution of the axial preload, and finally to produce an optimum configuration. While most of the axial separation force is supported through the axial preload along the inner leg and a clamp along the terminal leg, the inward force is reacted by the wedging of the magnet and the bucking from the bucking cylinder. To simplify the parametric study, an ideal model was constructed with the following two assumptions: the magnet is axisymmetric and the split on the outer leg is neglected. The parametric studies are performed on an ideal model. First, two different sizes of bucking cylinders (2.4 cm diameter and 4.8 cm diameter) were considered. The resulting temperature along inner leg and maximum Von Mises' stresses are shown in figures 3 and 4. The smaller bucking cylinder reduces peak temperatures and stress in the inner leg region. This is attributed to better current penetration and larger wedging area for the magnetic and thermal loads to react. The typical magnetic load profile is shown in figure 5.

Figure 2. ITD current profiles -- simulated and ideal

Figure 3. Temperature at inner and outer diameter of inner leg for two various holes: 2.4 and 4.8 cm diameter

Figure 4. Peak von Mises' stresses for various bucking cylinder diameters: 2.4 and 4.8 cm

On material selection for the bucking cylinder, three properties are considered: stiffness, strength, and thermal expansion coefficient. Three materials (beryllium copper, stainless steel, and tungsten) are chosen based on the different aspect of the respective properties. The resulting maximum Mises' stresses for each material are roughly the same as shown in figure 6. Consequently, beryllium copper was chosen for the bucking cylinder simply because it eliminates thermal expansion mismatch during the precooling of the magnet to liquid nitrogen temperature.

An optimum axial preload magnitude study was also conducted. The magnitude of axial preload is varied from 40, 50, 70, and 80 ksi, and the resulting Mises' stresses are shown in figure 7. An optimum magnitude for the axial preload appears to be 50 ksi. From the analysis above, a promising magnet configuration would have a 2.4 cm diameter beryllium copper bucking cylinder and 50 ksi axial preload along inner leg.

Figure 5. Typical magnetic forces

Nonideal Conditions

After determining fundamental parameters, a detailed analysis including nonideal effects; stack-up tolerance and split on outer leg was conducted. Since the ratio of inner radius to outer radius of the inner leg is small, the principle supporting mode is wedging. First, a magnet with 0.001 in. stack-up tolerance per pair of plates, being supported in pure wedging, was analyzed. The maximum Von Mises' stresses in the magnet shown in figure 8 has exceeded the material yield strength. It is obvious that partial bucking support is necessary to lower the stress level in the magnet. In order to assure the magnet is not in pure bucking, which results in stresses twice as high as in pure wedging; the size of bucking cylinder is crucial. The radial gap between magnet and bucking cylinder is sized to allow inward magnetic radial forces to close the stack-up tolerance of the magnet without contacting the bucking cylinder. On the other hand, the radial gap should be small enough to assure the bucking cylinder will contact the magnet and provide bucking support during the higher magnetic load period. Concentricity is maintained between the bucking cylinder and TF coil by use of a low stiffness material. The radial gap is chosen to be the average value of the radial displacement due to stack-up tolerance and total radial displacement for pure wedging.

The maximum Mises' stresses for the combined bucking and wedging stress state are shown in figure 8. Peak stresses are reduced to acceptable levels. An accurate estimate of stack-up tolerances is critical for the successful management of the bucking and wedging stress state. A low current discharge test will be performed on the assembled magnet without the bucking cylinder to predict the stack-up tolerance by measuring the radial displacement.

4501.0049

Figure 6. Peak von Mises' stresses for three different materials: stainless steel, tungsten, and beryllium copper

4501.0050

Figure 7. Peak von Mises' stresses for various axial preloading, 40, 50, 70, and 80 ksi

4501.0039

Figure 8. Peak von Mises' stresses in prototype TF coil -- wedging, and bucking and wedging

TF Magnet Fault Analysis

The prototype TF magnet consists of six sectors which are powered by the six HPGs individually. The concern about the effect of fault on the magnet structure are addressed. Three possible fault scenarios of the generators are:

1. one or more generators have nonequal voltage
2. one or more generators do not discharge due to no excitation field
3. one or more closing switches do not close.

Fault condition #2 where a generator fails to discharge due to no excitation field is the extreme of fault condition #1. In the event of no excitation field, interlocks within the HPG control system prevent the discharge from proceeding. In the prototype TF coil experiment, the inductive coupling between sectors is so small compared with overall inductance of the circuit that the effects on the currents in adjacent sectors are neglected. But the effect should be considered for a full-scale experiment. When little or no current flows in a particular sector as in fault condition #3, it produces no inward radial forces. Assuming the magnet acts as a unit, the net unbalanced inward radial force try to move the whole magnet toward one side. This unbalanced force either is transmitted to the busbars and/or can be balanced by frictional force between the preloading structure and the magnet. The required friction coefficients to provide enough frictional force to counter the unbalanced force under 50 ksi axial preload are listed in table 1 for various combinations of extreme current unbalance.

Table 1. Unbalance forces and required friction coefficients for various combinations of extreme current unbalance

Open Circuits		Unbalanced Force (MN)	Friction Coefficient
Number	Position		
1	Any	170	0.203
2	Next	294	0.351
2	Skip One	170	0.203
2	Skip Two	0	0
3	Next	340	0.406
3	Skip One	0	0

Conclusion

From electromechanical analysis, the ITD holds the promise of confirming the ability to generate and to maintain the high toroidal magnetic field in the necessary geometry required to produce fusion by ohmic heating alone. The analytical computer model's predictions of displacements, temperature rise, and field level will be compared to actual measurements, proving the complex model.

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