**DESIGN OF A PROTOTYPE 20 TESLA, SINGLE TURN, TOROIDAL
FIELD COIL FOR THE FUSION IGNITION
EXPERIMENT (IGNITEX)**

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DESIGN OF A PROTOTYPE 20 TESLA, SINGLE TURN, TOROIDAL FIELD COIL FOR THE FUSION IGNITION EXPERIMENT (IGNITEX)

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Abstract

The electromagnetic design of the fusion ignition experiment (IGNITEX)[1] combines unconventional pulsed power and magnet technologies. The experiment should produce an ignited plasma in a relatively simple and low cost way.[2,3] The proposed IGNITEX toroidal field (TF) coil is a 20 T, single turn, toroidal magnet powered by homopolar generators (HPGs). In order to demonstrate the magnet technologies, the Center for Electromechanics at The University of Texas at Austin (CEM-UT) is building a 0.06 scale prototype toroidal field coil to be powered by an existing 60 MJ, 9-MA, HPG power supply. This element of the Ignition Technology Demonstration (ITD) program is funded by the Texas Advanced Technology Program and the Texas Atomic Energy Research Foundation.

Introduction

The primary objective of the ITD is to demonstrate the operation of a low cost, 20 T, single turn, toroidal coil powered by homopolar generators in parallel. In addition, operation of this prototype magnet will permit verification of the computer models, material properties, and fabrication procedures. The prototype TF coil will approximate predicted levels of temperatures and stresses of the full-scale IGNITEX TF coil. The ITD experiment will be powered by an existing, fully operational, 60 MJ, 9-MA, HPG power supply located in the CEM-UT laboratory.[4]

This paper describes the design of ITD and its relevance to the full scale IGNITEX TF coil. Selection criteria for the high strength conductor alloy are discussed. Elimination of turn-to-turn electrical insulation in the single turn design permits better utilization of the available inner leg area for stress and thermal management. It is therefore possible for the magnet assembly to have physical properties very close to that of the conductor alloy. Fabrication and assembly procedures are essential ingredients to the success of the IGNITEX TF coil demonstration. A discussion of fabrication and assembly techniques is included. The design of the preload structure, the cryostat and the busbar system are described.

Description of Experiment

A prototype IGNITEX TF coil is currently being fabricated at CEM-UT. The TF coil experiment consists of all the necessary components required to demonstrate the operation of a 20 T, single-turn, TF coil powered by HPGs. Homopolar generators, designed, developed and operated by CEM-UT have been used for driving various pulsed power loads since 1973.[5] The Balcones HPG power supply (fig. 1) consists of six, drum type, 10-MJ generators, each rated at 100 V, 1.5 MA for a combined parallel output configuration capability of 9 MA at 100 V.

To extend the operational time of the TF coil, it is precooled to liquid nitrogen temperature. The magnet is pool cooled in a fiberglass reinforced cryostat. Heat is applied to the busbars between the TF coil and the HPGs to prevent condensation from forming on the generators.

High magnetic and thermally generated stresses in the inner leg of the TF coil are negated by applying an axial preload. Preload requirements for the 0.06 scale are 420 tons in order to maintain an average axial compressive load of 50 ksi over the inner leg area of the coil. The preload is applied hydraulically to the inner leg of the TF coil via a composite thermal compression spacer at the top and bottom of the coil. An external frame provides the axial containment and is also used to support the structure. The hydraulic

system must maintain the preload through the discharge, compensating for axial strain and thermal growth. A second preload is applied radially at the top and bottom of the TF coil to hold the coil sectors together. The radial preload is applied by two rings which are thermally assembled over the coil sectors.

- six 10 MJ homopolar generators
- each rated @ 100 V and 1.5 MA
- series or parallel combinations ranging from 600 V @ 1.5 MA to 100 V @ 9.0 MA
- 2 to 5 minute rep rate

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Figure 1. Balcones homopolar generators

The ITD experiment will be located in the base of the CEM-UT HPG pit permitting the busbars to feed the device from above (fig. 2). This arrangement simplifies the liquid nitrogen cryostat by eliminating cryogenic seals on the busbars. The TF coil, consisting of six, 60° sectors will be connected to the six HPGs in a parallel configuration as shown in figure 3. Although access to the ITD experiment will be limited by locating it in the HPG pit, the location minimizes the length of bus between the generators and the TF coil and by designing a removable joint in the busbars, permits other experiments above the pit to utilize the generators.

Selection of the scale for the TF coil is based on the ratio of the current capability of the Balcones HPG system to the current requirements of IGNITEX's TF coil--9 MA/150 MA or 0.06 scale. To produce the same 20-T toroidal field, the magnet dimensions are reduced then by this factor. A pulse transformer was considered to step up the generator current to accommodate a larger scale but inefficiencies in the transformer and excessive cost made this option unattractive. In addition, directly coupling the TF coil to the HPGs is more representative of the full scale IGNITEX. A second prototype with a scaling factor of 0.12 will succeed the 0.06 scale prototype and will operate at 10 T when driven directly with the HPG power supply.

The 0.12 scale TF coil is intended to demonstrate scaling relationships as well as serve as the load for a proposed 1 GJ homopolar module[6]. Operating parameters for the Technology Demonstrator and the full scale IGNITEX are given in table 1.

Figure 2. 0.06 ITD buswork, magnet, and preload structure

Figure 3. ITD power supply layout

Table 1. Critical parameters of IGNITEX toroidal field coils

	IGNITEX TF COIL	TECHNOLOGY DEMONSTRATION (0.06 scale)
MAGNETIC FIELD ON AXIS	20 T	20 T
MAJOR RADIUS	1.5 m	9 cm
TF COIL MINOR RADIUS	0.605 m	3 cm
TF COIL ASPECT RATIO	2.48	3
CURRENT PULSE WIDTH	10 s	100 ms
PEAK CURRENT	150 MA	9 MA
AVG. CURRENT DENSITY (INNER LEG)	63 MA/m ²	829 MA/m ²
MAXIMUM STRESS (von Mises)	98 ksi	96 ksi
PEAK TEMPERATURE	237 C	220 C
MATERIAL	BeCu (C17510)	BeCu (C17510)
NO. OF SECTORS	12	6

1229.4

Even though current density in the TF coil is a function of the square of the scaling factor, stresses scale linearly assuming all dimensions have been scaled linearly. In addition, as long as the time scaling factor is the square of the geometric scaling factor, the temperature, magnetic induction, and Mises stresses in the scaling model are an image of those for the full-scale model. Ideally, we

would like the physical history of the prototype to scale exactly to the full scale IGNITEX but the existing circuit parameters of the BHPG system prevent this. Due to the geometry and layout of the existing busbars in the HPG pit the circuit parameters of this experiment are for the most part fixed. The inductance of the HPGs and the bus leading up to where the TF coil will be attached dominate the equivalent inductance for the circuit. Note that the TF coil aspect ratio of the prototype is larger than the full-scale coil. This feature compensates for the effects as the result of a longer current pulse. A scaled pulse for the 0.06 scale TF coil would be 36 ms long with an 18 ms flat-top as shown in figure 4. A simulated HPG discharge current profile is superimposed showing an estimated pulse width in excess of 100 ms. The additional energy in the TF coil drive temperatures and stresses to levels that are representative of those in the IGNITEX TF coil with a correct TF coil aspect ratio. Should the actual circuit inductance exceed those estimated for the generation of the current profile, a dump circuit may have to be included to reduce the energy in the coil.

Figure 4. ITD current profiles--simulated and ideal

TF Coil Design

A single turn TF coil's unique feature is the elimination of turn-to-turn insulation. The additional conductor material in the inner leg region of the coil helps in managing the high magnetic and thermal loading. Selection of the magnet conductor is based on trade-offs between electrical conductivity, yield strength, material stability and available plate thickness. Primary candidates for the IGNITEX TF coil at this time are beryllium copper (C17510) and dispersion strengthened copper (C15715). A comparison of a few physical properties of the two alloys (in plate form) is given in table 2. The prototype TF coil is being built using 1.25 in. thick plates of beryllium copper (Brush Alloy #3 HT). As one would expect, using BeCu results in stresses and temperatures higher than with dispersion strengthened copper (DSC) but they are within the materials capability. Due to the high degree of cold work required for the DSC, plate thicknesses are limited and dimensional stability is impaired. Nevertheless, the high electrical conductivity of DSC is attractive enough to continue considering it as a potential TF coil conductor alloy especially since a large portion of the stresses in the TF coil are thermally induced.

The electromechanical analysis of the single turn coil consists of the use of a finite element program (TEXCOR)[7] to solve a set of coupled electrical circuit, magnetic, and thermal diffusion equations with temperature dependent properties. TEXCOR provides temperatures and magnetic body force densities for a three dimensional, finite element stress analysis of the magnet structure[8]. Use of beryllium copper for the ITD TF coil results in a peak Mises stress of 86 ksi at peak electromagnetic loading. Thermally generated stresses at the end of the pulse are more severe. Figure 5 shows a peak Mises stress of 96 ksi at the end of the pulse which coincides with a peak temperature of 220°C at the od of the inner leg.

Axial forces are supported by the axial preload along the inner leg and by clamps along the terminal leg. The terminal clamp provides both the axial support for the outer leg and clamping

Table 2. Physical properties of high strength copper alloys

PROPERTY/ALLOY	DISPERSION STRENGTHENED COPPER AL-11	BERYLLIUM COPPER ALLOY A3 HT
Thermal Expansion (in./in./°F 10×10^{-4}) ^a	10.9	9.8
Conductivity @ Room Temp. (%IACS)	92	64
Conductivity Ratio (Cond. LN ₂ /Cond. Rm. Temp.)	4.6	2.3
Thermal Conductivity (W/M - K) ^a	365	249
Specific Heat (J/kg - K) ^a	385	334
Yield Strength (ksi) ^a	67	108
Modulus of Elasticity (Msi)	19	20
Percent Cold Work Required (%)	75	37
Max. Plate Thickness (in.)	0.63	2.25

^a room temperature properties

1225

Figure 5. Peak Mises stresses in prototype toroidal field coil—pure wedging and bucking and wedging

pressure for the electrical joint between the TF coil terminals and the buswork. A ring-type clamp on each individual TF coil plate as shown in figure 6 maximizes both the clamp area and conductor area. Clamping pressure is produced by wedge jacks located above and below the terminals. A finger joint design is also utilized to provide adequate contact area at the joint. Ceramic spacers located between the TF coil terminals and between the terminals and the clamp provide electrical insulation and negate thermal contraction differences between the clamp and the terminals during cool down.

TF Coil Stress Management

Inward radial forces on the tapered coil plates causes the plates to "wedge" against each other while the inward radial force also causes each plate to "buck" against the central support post. The ideal operating stress state for the single turn TF coil is one which utilizes a combination of "bucking and wedging" with emphasis in the wedging. Uncertainties in a TF coil's design such as a compliant magnet structure, gaps between plates and thermal gradients inhibit achieving an optimum balance. The single turn TF coil features that help in minimizing non-ideal effects are: 1) a well characterized and "noncompliant" material in the inner neck region of the TF coil as a result of eliminating turn-to-turn insulation, 2) a minimum tolerance "stack-up" in toroidal plate assembly, and 3) a solid bucking cylinder in which the shape and material properties may be selected to best suit the combined stress state at peak loading.

Figure 5 shows Mises stresses for the pure wedging and the combined stress state of bucking and wedging. A pure wedging stress state is much more desirable than pure bucking but stresses close to peak electromagnetic loading still exceed the yield strength of the material. In order to assure the magnet is not in pure bucking, which results in stresses twice as high as in pure wedging, correct sizing of the bucking cylinder is crucial. The radial gap between magnet and bucking cylinder is sized to allow inward magnetic radial forces to close the toroidal stack-up tolerances of the magnet without contacting the bucking cylinder. On the other hand, the radial gap is small enough to assure the bucking cylinder will

contact the magnet and provide bucking support during the higher magnetic load period. 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. Concentricity is maintained between the bucking cylinder and TF coil by use of a low stiffness material. An accurate estimate of the toroidal stack-up tolerance is critical for the successful management of the bucking and wedging stress state. Low current discharge tests will be performed on the assembled magnet without the bucking cylinder to measure radial displacements due to toroidal stack-up tolerances.

Figure 6. Terminal connections

TF Coil Fabrication and Assembly

The toroidal field coil assembly incorporates six, 60° sub-assemblies. One TF coil wedge is machined from a 1.25 in. thick BeCu plate. Equal amounts of material are removed from each side of the plates in an attempt to prevent the plates from distorting. The plates are machined to an angle of 10°1' so that when stacked in the 60° sub-assemblies, they may be remachined to eliminate angular tolerance stackups. Six TF coil plates of a 60° sector are stacked together and for ease of assembly the plates are temporarily bolted together (fig. 7). At this point in the assembly, instrumentation is installed with the leads extending through the terminal gap in the outer leg of the TF coil. Magnet instrumentation will measure field levels, total current and current gradients within a sector, temperature rise, and displacements. Electrical insulation between TF coil sectors consists of a 1/2 mil sheet of Mylar® to break up eddy currents in the longitudinal direction. Three of the 60° sectors are bolted together and the two exposed surfaces are machined planar to each other. Once this is done to both halves of the TF coil, the two sections are assembled. The final assembly of the toroid has only the flatness tolerance stack up; angular tolerances are negated by this assembly technique. The bore of the TF coil is filled with a foam filler material to displace liquid nitrogen and prevent over pressurizing this volume during a discharge. An assembly fixture is used to support the six coil sectors and to machine the radial and axial preload surfaces. The two radial preload rings are then thermally assembled around the TF coil and the bore of the coil may be machined. Here again, BeCu has been selected for the material for the radial preload rings primarily to match thermal expansions during cool down. The bucking cylinder may be machined and installed after low current tests are performed to characterize magnet radial displacements.

Preload System

Axial preloading of the magnet is to be accomplished with a hydraulic clamping structure. The structure is to be in a relaxed state during chilling, and will apply the appropriate preload force to the magnet after equilibrium temperature is reached. The preload force will be applied throughout the pulse and will remain applied for a short period afterwards. The structure must therefore maintain the preload force within tolerances during electromagnetic loading and thermal growth of the magnet.

The mechanical arrangement of the preload system consists of an assembly of compressive elements which concentrates axial force on the magnet upper and lower faces, an outside structure which transmits the preload force in tension, and a hydraulic extension element. The compressive elements of the system include the contact discs, two load concentrators in series, and a spherical bearing used

• 36 ea, 10° 5', TF coil plates

• 6 TF coil plates bolted together to form 60° sector

• 3 sectors clamped together to form 180° of torus

sector insulation installed

Bore instrumentation installed

- HP
- Temp
- Strain
- Rogowski

slot compression spacers installed & instrumentation terminated at O.D.

• 180° halves clamped in radial clamping fixture on vertical turret lathe

buckling cylinder bore machined

axial preload surfaces machined

steps machined for radial preload rings/ radial preload rings shrunk on

conductor contact surfaces machined

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Figure 7. TF coil assembly procedure

for alignment. The outside structure consists of upper and lower monolithic plates loaded in bending connected by six vertical links loaded in tension. The hydraulic elements are five, high-pressure hydraulic cylinders arranged under the top plate. The two plates are connected by six vertical links; these links are held to the plates by twelve commercially available spherical bearings. The link/plate joints are designed such that during assembly and prior to preloading, the links act as standoffs. Upon preloading, the spherical bearings allow the plates to deflect angularly without imposing a bending moment on the links.

Liquid Nitrogen System

A cryostat will surround the magnet with a bath of liquid nitrogen (LN^2) in order to chill the magnet prior to pulsing. The LN^2 system must chill the magnet from room temperature and maintain thermal equilibrium prior to pulse. Because of the monolithic design of the magnet, it will contain low thermal resistance and the chilling process will be rapid. Thermal loading after initial chilling will be caused by conduction through the busbars. The LN^2 must be delivered to the cryostat with a flowrate sufficient to balance the thermal loads of initial chilling and bus conduction.

The six busbar structures connected to the magnet emerge from the LN^2 bath and connect to the main buswork of the power supply. Explosive closing switches are integrated into these busbars. In order to prevent condensation from forming near the explosive switches and generators, a busbar heating system will be utilized which will maintain room temperature at the switches. This heating system will consist of flexible Si-Rubber etched foil heaters attached to the coaxial portions of the busbars, temperature sensors installed near the explosive switches, and a time-proportioning temperature controller.

Busbar and Closing Switch Design

A busbar from each generator will feed each TF coil 60° sector from above, simplifying the LN^2 cryostat by eliminating busbar feed-throughs. A coaxial portion of each busbar provides low inductance, ample surface area for frost controlling heaters, and a geometry which integrates well with a coaxial closing switch.

Aluminum was selected as the busbar material for its properties of conductivity, strength, weldability, machinability, and flexibility. Although electrical conductivity is lower for the aluminum than for copper, the additional resistance is necessary to dampen the circuit and prevent the generators from ringing. Conductor cross-sectional area is sized to provide strength and minimize resistive heating. As determined in a finite element analysis, thermal contraction of the nitrogen chilled TF coil exerts tensile force and significant bending stresses in the busbars. The selection of aluminum, which has a lower Young's modulus than copper, reduces stresses by adding flexibility. The aluminum also requires less structural reinforcement to support the magnetic repulsion pressures of up to 3000 psi. Aluminum welds on each end of the outer coax can be heat treated to provide excellent strength.

Each HPG and 60° sector will be in series with a discharge-initiating explosive closing switch. Brushes of the generators, which pneumatically actuate in 25 ms with jitter of ± 5 ms, are designed to initiate discharges into high inductance loads. They consequently have a maximum di/dt rating of 8 MA/s limited by localized heating. The ITD experiment requires a faster switch for its di/dt of 50 MA/s and time to peak of 30 ms. An existing coaxial explosive switch with a demonstrated di/dt of 5000 MA/s and a closing time of 80 μ s with a jitter of ± 15 μ s will be scaled up to accommodate the action integral ($\int i^2 dt = 11 \times 10^{10} A^2 s/generator$) of the ITD pulse. The existing switch, frequently used in railgun experiments, consists of an expendable copper ring which is explosively wedged into a tapered annulus made up of two steel catching rings. As current flows from inner to outer conductor, magnetic pressure assists in providing contact pressure between the rings. The switch has successfully carried 1.14 MA[9].

Conclusion

Test results from the ITD program will accomplish several things. First, the analytical computer model's predictions of displacements, temperature rise and field levels will be compared to actual measurements, proofing the complex model. Secondly, fabrication techniques and assembly procedures developed for the prototype may be applied to the full scale IGNITEX. Finally, the IGNITEX Technology Demonstrator will validate the technology to generate a 20 T toroidal magnetic field using homopolar generators as the power supply.

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