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Abstract: Very high toroidal magnetic fields have been produced using a single-turn magnet powered by homopolar generators (HPGs). A design goal of a 20 tesla confinement field has been met by the combination of a low impedance toroidal magnet, a high current, low voltage power supply, and the use of a high strength, high conductivity copper alloy. The Ignition Technology Demonstration (ITD) is a 1/16 scale prototype of the proposed full-scale IGNITEX (Ignition Experiment) toroidal field (TF) magnet. Stresses and temperatures reached in the prototype TF magnet are representative of those that would be experienced in a 1.5-m major radius magnet with a 5 s flat top current profile.

Synchronized, parallel operation of multiple homopolar generators into a single-turn toroidal magnet has been realized. The prototype TF magnet has produced toroidal magnetic fields up to 18.1 T on-axis with liquid nitrogen (LN2) precooling and axial preloading of the magnet. Room temperature operation of the magnet has produced on-axis fields up to 11.5 T and with LN2 precooling only, up to 15.4 T. Peak current from the HPG system for the 18.1 T test was 8.14 MA with an open circuit voltage of only 49 V. Generator synchronization is achieved by six, 1.5 MA rated, closing switches with a maximum jitter of 10 μ s. A peak current density in the inner leg region of the TF magnet of 750 MA/m² was experienced during the 18.1 T test. Peak temperature in the inner leg region for this test was measured to be 135°C. The description of the ITD experiment, operational experience, and test results are presented.

INTRODUCTION

The original concept for the IGNITEX ignition experiment was proposed by M.N. Rosenbluth, W.F. Weldon, and H.H. Woodson [1] along the lines of B. Coppi's proposal [2] for a compact thermonuclear ignition experiment. The IGNITEX experiment proposed to use unconventional tokamak coils and power supply technologies based on concepts of high-current systems developed by the Center for Electromechanics at The University of Texas at Austin (CEM-UT). A 20 T, on-axis, toroidal magnet is not a new concept [3]; however, to this author's knowledge, one has never been demonstrated. The single-turn, toroidal magnet experiment was conceived to demonstrate critical technologies and thereby minimize the risk of pursuing a full-scale, fusion ignition experiment.

The design intentions of the TF magnet demonstration were to reproduce temperatures and stresses that would occur in a 1.5 m coil (the original IGNITEX major radius) with a 5 s flat top current profile.[4] Operating parameters for the prototype TF magnet and the original IGNITEX TF magnet are given in table 1. The magnet has a TF aspect ratio of 3.0 and a major radius of 9 cm. A high strength, high stiffness design was achieved by stacking 36,

wedge shaped beryllium copper (Brush Wellman Alloy #3HT) plates (without insulation) to form the torus. High flatness tolerances and intermediate machining steps minimize assembly tolerance stack-ups. The lack of electrical insulation in the toroidal plate stack-up gives the coil a high percentage of conductor material in the critical inner leg region. The result is mechanical and thermal limitations dictated by the conductor material only. The coil design utilizes wedging as the predominate stress-management technique, but does require a "bucking post" at high fields. The radial gap between the coil and the bucking post is sized to allow inward magnetic radial forces to close toroidal gaps before contacting the bucking cylinder. To achieve 20 T on-axis, the inner leg of the magnet must be preloaded and it must be precooled to LN2 temperature. High busbar forces are managed by common techniques of clamping, preloading, and sensible use of materials and geometry to manage the electromagnetic loads.[5]

Table 1. Operating parameters for the prototype TF magnet and the original IGNITEX TF magnet

	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	3.0 m
TF Coil Aspect Ratio	2.48	3
Current Pulse Width	10 s	150 ms
Peak Current	150 MA	9 MA
Avg. Current Density (Inner Leg)	63 MA/m ²	829 MA/m ²
Max. Stress (von Mises)	93 ksi	90 ksi
Peak Temperature	180°C	187°C
Material	BeCu (C17510)	BeCu (C17510)
Number of Sectors	12	6

An existing 60 MJ HPG, 9 MA power supply located in the CEM-UT laboratory fulfills the low voltage, high current, power supply requirements. The 60 MJ HPG system consists of six, 10 MJ generators each rated at 1.5 MA, 100 V open current (fig. 1). The TF magnet (consisting of six, 60° sectors) is connected to the six HPGs in a parallel configuration. To accommodate the fast current rise time of the HPG/TF magnet circuit, each HPG and 60° sector is in series with an explosive closing switch. Typically, the HPG brush gear is used as the making switch when discharging into inductive loads. A coaxial explosive closing switch was designed based on an existing, highly reliable switch used on other pulsed power experiments.[6] Due to the high demand on the 60 MJ HPG system from other experimental programs and the need to minimize circuit impedance, the TF magnet experiment was located below

Figure 1. Prototype toroidal magnet and 60 MJ homopolar system layout

ground level in the center of the generator pit. An axial magnet preloading system and a LN2 supply and exhaust system were incorporated into the magnet/generator pit design. The diagnostic system for the TF magnet prototype is designed to determine strain, temperatures, and magnetic fields at several locations in the TF magnet.[7] These values are used to verify numerical predictions by electromechanical and thermomechanical analyses.[8]

Preliminary tests in the summer, 1990 resulted in a busbar failure during a 15 T experiment. The program continued and was able to perform a successful 18.1 T test before succumbing to funding deficiencies in April 1991. This paper presents operational experiences and test results for the prototype, single-turn, TF magnet experiment.

OPERATION OF THE EXPERIMENT

Operation of the TF magnet proceeds with the loading of the explosive closing switches. Switch loading and unloading proved to be the most time consuming aspect of the testing program. Several hours are needed to complete this task. LN2 pool-cooling of the magnet proceeds once the switches are loaded and an HPG system checkout run have been completed. Busbar heaters and the nitrogen exhaust system are enabled at this time. The exhaust system in the HPG pit prevents excessive oxygen dilution due to the nitrogen boil-off. So as to prevent an excessive thermal gradients in the magnet or adjacent busbars, nitrogen gas is used initially to slow down the process. LN2 flow to the cryostat is controlled by an LN2 level sensor/solenoid valve. The cool-down process requires about 150 gallons of LN2 and takes approximately 45 minutes. During this time, final checks and preparations are made on the data acquisition system. Once the magnet reaches temperature, the hydraulic, axial preload is applied and the motoring sequence for the six HPGs is initiated. Busbar heaters are disabled just prior to the discharge. A prerequisite for the HPG control system to permit a discharge is that the generator speeds match to within a specified tolerance window. Figure 2 shows a typical HPG/TF magnet operating sequence. To operate the power supply,

the operator need only to provide input selection of the desired generator's speed and field current level.[9] Any variation in the HPG/TF magnet sector circuit parameters may be compensated by adjusting the respective HPG's field voltage. In this way, a sector-to-sector field ripple may be corrected. This optional adjustment has not been necessary with the prototype magnet. After a discharge, busbar heaters are reenabled and the magnet is brought back up to room temperature.

TF MAGNET TESTING

The testing program of the HPG/TF magnet system consists of three phases: low current, room temperature testing ($B \leq 11$ T); intermediate current with LN2 cooling testing, ($B \leq 15$ T); and high current with LN2 cooling and axial preloading testing ($B \leq 20$ T). A summary of the tests #10 through 21 are given in table 2. Tests #1 through 9 (5/90-7/90) consisted of room and LN2 temperature tests up to 15 T. Since tests #1 through 9 were previously reported on [10], they are omitted here for space considerations.

Figure 2. Typical HPG/prototype TF magnet operating sequence

TEST #10—BUSBAR LEAD FAILURE

A mechanical failure of the aluminum magnet leads which clamp to the TF magnet occurred during a high current test (test #10—8/17/90) utilizing LN2 precooling and the hydraulic press. Current and voltage profiles during the test were nominal up to the point (1.10 MA/HPG, 14.7 T) when the outside bus leads and steel backup plate on one of the sectors fractured and open-circuited. In a cascading effect, the other five busbar sets experienced similar breakage and the magnet realized no significant damage. Postmortem analysis of the failed region showed a high bending stress in the reduced cross section region near the magnet/bus lead clamped joint. This stress is the result of

Table 2. Summary of prototype TF magnet tests

Test No.	Room Temp Tests			LN2 Cooled Tests			Testing with Hydraulic Preload on Magnet				
	11	12	13	14	15	16	Room Temp		LN2 Temp		
Date of Test	3/13/91	3/14/91	3/15/91	3/20/91	3/21/91	3/22/91	4/4/91	4/5/91	4/8/91	4/9/91	4/10/91
HPG Speed (rpm)	375	1,275	1,800	1,190	1,712	2,300	1,275	1,750	2,325	2,550	2,900
Average Open Circuit Voltage (V)	6.2	21.7	30.5	20.1	29	39.1	21.2	29.9	39.5	43.4	49.3
TF Magnet Field (T)	2.0	8.1	11.5	8.2	11.9	15.4	8.0	12.0	15.5	16.6	18.1
Peak Generator Current (kA)	150	600	890	618	889	1,155	600	903	1,165	1,250	1,356
Total Current (MA)	0.90	3.60	5.30	3.70	5.30	6.93	3.60	5.40	7.00	7.50	8.14
Maximum Measured Temperature (°C)	24	60	140	-145	-86	-4	84	-76	-4	55	135
Hydraulic Preload on Inner Leg of Magnet (ksi)	0	0	0	0	0	0	25	25	25	35	45

magnetic separation forces acting on the angle section of the outer lead. Several modifications were made to the busbar leads. These modifications are presented in detail in reference.[5] An interesting aspect of the failure is that the current level per generator at the time of failure was actually lower than the previous test (test #9—15.0 T). An additional detail about test #10 is that the explosive switch of sector #5 showed severe arc damage. As we would learn later, a current distribution problem existed in the explosive switch design and could have initiated the switch failure. It is now well known from the detailed analysis that the leads were underdesigned, but one possible explanation for the failure to have occurred at a lower current level than the previous test would be the unbalanced loading from a closing switch failure.

TEST #16—SWITCH FAILURE

During test #16 (LN2 cooled, 15.4 T), the explosive closing switch of generator #1 failed open after reaching peak current. Close examination of the failed switch and the other five switches revealed what appeared to be a current distribution problem within the switch. Weld spots and arc damage were noted to be more predominate at the top of the switches. A two step modification was initiated that required only a few days to implement. First, an insulating current diverter was installed at the top of each switch to force current to the lower quadrants of the switch. Secondly, the electrical resistance to the lower sections of the switch was reduced by adding a copper distribution ring to the switch assembly. The closing switches showed no signs of welding or arcing for the remaining tests. Although the circuit opening test #16 was not intentional, it provided valuable HPG/TF magnet fault data showing the inductive coupling between the magnet sectors. The HPG/TF magnet sector currents for test #16 close to peak show that as the current in sector #1 drops off, the adjacent sector currents rise by approximately six percent while sector #4 (directly opposite to sector #1) shows very little effect.

HIGH CURRENT TESTS #17 THROUGH 21

Prior to the TF magnet tests utilizing the axial preload structure, the preload structure was carefully aligned and preloaded against the magnet. The preloading of the structure is necessary to compensate for thermal and mechanical strains that occur during operation. The axial magnet inner leg strain gages and the press hydraulic pressure are monitored in real time in the HPG control room.

With 45 ksi (90%) preload on the magnet and 6,030 psi hydraulic cylinder pressure, the axial strain variation from sector-to-sector was measured to be only 4.8%.

For space considerations, current, voltage, and Hall-probe data are shown for test #21 only. Test #21 resulted in an on-axis toroidal field of 18.1 T and a record current output for the HPGs for a total of 8.14 MA. Homopolar instrument brush voltages and individual current profiles for test #21 is shown in figure 3. The circuit is slightly underdamped resulting in a rotor reversal of 175 rpm for test #21. Although the 10 MJ HPGs were not designed for bidirectional operation, this level of reversal is not damaging to the machines.

The on-axis Hall probe data from test #21 (fig. 4) was produced using F.W. Bell Hall generators (BHT-921) calibrated with a 5 cm, 20 T, bitter magnet at the MIT, National Magnet Laboratory. The majority of the previously expected radial positioning error of the probe mounts was eliminated by a new mount design, but a measured magnetic field error of 3% at 18 T persists. This measurement error may still be the result of 1) Hall probe mount positioning, 2) inductive coupling of the instrumentation leads, 3) a circularity error of the magnet bore, or a combination of all three.

Figure 3. Six HPG voltages and currents for 18 T test (test #21)

TF magnet tests #20 and 21 show maximum measured temperatures of 55 and 135°C respectively. Maximum predicted temperatures for tests #20 and 21 were 61 and 109°C. Prior to tests #20 and 21, measured magnet temperatures have been consistently lower than predicted. The consistently low measured temperatures

are believed to be the result of thermocouple response time and the conservative assumptions associated with the computer model. As temperature change increases with higher field levels, the thermocouple response time should contribute less to the measurement error. An explanation for the high temperature measured for the last two tests may be due to the magnet not being entirely at LN2 temperature prior to the discharge. This is confirmed by the initial magnet temperatures shown in figure 5 which show a wider range of initial temperatures than previous LN2 cooled test.

Figure 4. TF magnet Hall effect generator data from 18 T test (test #21)

During a routine inspection of the magnet and busbars after test #21, one of the 72 wedge jacks which clamp the busbar leads to the magnet terminals was found to be loose and an adequate torque could not be retained. Attempts to tighten the lower jack with minimal disassembly of the busbar system failed. The problem remained with the upper jack, which as a result of the busbar geometry could not be easily accessed. Magnet tests could not continue with a defective terminal clamp, so the busbar system and upper hydraulic press components were disassembled.

The 0.25 in. bolt that is used to tighten the upper wedge jack was found to have stripped as a result of insufficient thread engagement. Apparently, the lower wedge jack was overtightened during assembly preventing the upper wedge jack from adequately engaging its threads. This problem is easily alleviated by either decreasing the insulation thickness or increasing the bolt lengths. The prototype magnet and magnet system components were removed from the generator pit until program funding could be reestablished.

CONCLUSION

The prototype TF magnet has produced toroidal magnetic fields up to 18.1 T on-axis with LN2 precooling and axial preloading of the magnet. Room temperature operation of the magnet has produced on-axis fields up to 11.5 T and, with LN2 precooling only, up to 15.4 T. Peak current from the HPG system for the 18.1 T test was 8.14 MA, with an open circuit voltage of only 49 V. A peak current density in the inner leg region of the TF magnet of 750

Figure 5. Inner leg temperature data from 18 T test (test #21)

MA/m² was experienced during the 18.1 T test. Peak temperature in the inner leg region for this test was measured to be 135°C. Although the toroidal magnet tests performed do not include the effects of an integrated poloidal field (PF) coil system or vacuum ports, these tests are a first step in developing a promising compact, high-field magnet system. Future plans include completion of toroidal magnet tests to 20 T with the existing prototype and the development of a large scale integrated TF and PF magnet system.

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