HIGH CURRENT TRANSMISSION AND SWITCHING SYSTEM FOR A PROTOTYPE, 20 TESLA, TOROIDAL MAGNET

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HIGH CURRENT TRANSMISSION AND SWITCHING SYSTEM FOR A PROTOTYPE 20 TESLA TOROIDAL MAGNET

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Abstract: The Ignition Technology Demonstration (ITD) is a 0.06 scale prototype toroidal field magnet of the proposed full-scale IGNITEX (Ignition Experiment) tokamak. The goal of ITD is to achieve an on-axis magnetic confinement field of 20 T while demonstrating the magnet's ability to withstand high magnetic and thermal stresses [1,2]. To accomplish this task, a peak current of 9 MA must be transferred from six balanced homopolar generator (HPG)/busbar circuits to the liquid nitrogen (LN₂) cooled magnet. HPGs are well suited for operation of single-turn coils because they are inherently high current, low voltage machines which can inertially store the energy required for a pulsed discharge. To date the system has delivered pulses of up to 8.14 MA to the toroidal magnet, producing an on-axis field of 18.1 T.

In order to properly synchronize current transfer, an explosive closing switch is employed for each of the six independent HPG/busbar circuits. The switches operate by explosively driving a scalloped copper ring into a tapered annular gap made up of two copper alloy rings. With a jitter time of 10 μ s, parallel circuit synchronization is better than 0.03% relative to the current rise time. The excellent performance of the switches during discharges of up to 8.14 MA is attributed to several design features which assure proper current distribution. Busbar design considerations have included electromagnetic loading, thermal gradients and magnet preloading effects. The switches and busbars have successfully operated at 82% of their rated action of $1.24 \times 10^{11} \text{ A}^2 \text{ s}$ per switch. Description of the ITD busbar/switching system, design improvements, and operational experience are presented.

INTRODUCTION

The IGNITEX concept proposes the use of a single-turn-coil tokamak to ohmically heat a plasma to thermonuclear conditions and thus produce and control an ignited plasma [3]. The presence of an on-axis toroidal field of 20 T for 5 s is instrumental in providing a high probability of ignition. The objective of the ITD is to demonstrate this high field technology at low cost using a scaled prototype and an existing HPG power supply. The 0.06 scale is based on the linear relation between the peak current capability of the power supply (9 MA) and the current required to produce a 20 T field in the full scale experiment (150 MA).

Due to the absence of turn-to-turn insulation, single-turn tokamaks have some inherent advantages over multiple-turn designs, but require higher currents to achieve the

same number of amp-turns. The need for a power supply is satisfied by the employment of HPGs, which are well tested and have established a high degree of reliability. The remaining requirement is for a high current, low impedance transmission and switching system. The development of this system for the prototype toroidal magnet has proven to be challenging but achievable.

TESTING

ITD testing consists of three phases: low current, room temperature testing ($B \leq 11.0 \text{ T}$); intermediate current with LN₂ cooling testing, ($B \leq 15.0 \text{ T}$); and high current with LN₂ cooling and axial preloading testing ($B \leq 20.0 \text{ T}$). Although the intermediate current testing phase was completed during the summer of 1990 [4], several lower current tests were repeated in 1991 after busbar design improvements were made. This was done to reestablish reliability in the busbar, closing switch, magnet, and data acquisition system before proceeding to the high current testing. Data from the 1991 series of tests is shown in table 1. Current and voltage waveforms from the 18.1 T test are shown in figure 1.

DESIGN OF HIGH CURRENT BUSBARS

Given the known characteristics of the HPGs, the predicted electrical parameters of TF coil, and the desired pulse shape of the experiment, the design requirements of the busbar system were deduced. While it was not feasible to create the flat-top pulse shape, characteristic of the actively controlled IGNITEX, it was possible to create a current contour which would induce equivalent stresses and temperatures in the ITD magnet [4]. Each of six identical busbars must simultaneously deliver a peak current of 1.5 MA, with a pulse width on the order of 150 ms and an action of about $1.24 \times 10^{11} \text{ A}^2 \text{ s}$, into a 60° sector of the LN₂ cooled TF coil. Inductance must remain low in order to minimize pulse width, while resistance should be high enough to provide a critically damped circuit. An overdamped circuit would result in excessive resistive heating of the TF coil, necessitating a dump circuit. An underdamped circuit would cause circuit "ringing". This is considered undesirable for these particular generators because of the possible brush gear damage due to rotor reversal, although small reversals have proven tolerable for the brush gear [5,6].

The six drum-type HPGs, each rated at 1.5 MA, are located in a hexagonal pit along with riser busbars which carry current to several floor level experiments. The induc-

Table 1. Summary of 1991 ITD TF magnet testing

	Room Temp Tests			LN2 Cooled Tests			Testing with Hydraulic Preload on Magnet				
	11	12	13	14	15	16	Room Temp		LN2 Temp		
Test Number	11	12	13	14	15	16	17	18	19	20	21
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

Figure 1. Six HPG voltages and currents for 18 T test (test #21)

tance and resistance of the riser busbars and the lack of floor level space dictated locating the ITD sub-floor in the hexagonal pit and centered below the HPGs. This location simplified the design of an LN₂ cryostat by allowing busbars to extend down from the HPGs into the open top of the cryostat, eliminating the need for cryogenic seals. However, busbar design and assembly were more difficult because of the confined space and limited connection options in the pit.

The busbar design (fig. 2) consists of two flat plate configurations on each side of a 23 cm (9 in.) outer diameter (OD) coaxial bus. A coaxial explosive closing switch is integrated into the first transition. Band heaters on the inner and outer coaxes prevent condensation from forming in the switches and HPGs [7]. A 5.12 MN (1.15 Mlb) hydraulic press provides axial preloading to the TF coil during high current tests. A steel structure, anchored to the hex pit structure and to the base plate of the hydraulic press, supports the experiment during testing and secures the hydraulic press after aligning it with the magnet. Before cooling of the magnet, jack bolts are used to raise the base plate against the magnet in order to preload the assembly. Preloading the support structure compensates for thermal and mechanical strain incurred during operation.

A finite element analysis (FEA) of the busbar assembly was performed to calculate thermomechanical forces during cooling. Solutions to this thermal model were combined with electromagnetic closed-form solutions to solve for peak stresses, which occur during peak current. 6061-T6 aluminum was chosen for the major busbar components based on its mechanical strength, electrical conductivity, and weldability (fig. 3).

The circuit as built was found to be slightly underdamped. The predicted rotor reversal during a 20 T experiment is 225 rpm, a safe level for the HPG brushes. Predicted maximum pulse width is 150 ms with an action of $1.24 \times 10^{11} \text{ A}^2 \text{ s}$. Although circuit inductance and resistance are time dependent, constant values of 460 nH and 21 $\mu\Omega$ closely model average values when used in an R-L-C circuit simulation [2]. The 10 MJ HPG models approximately as a 2,000 F capacitance. A breakdown of the average values are given in table 2.

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Figure 2. Sectional view of ITD busbar with current path

Table 2. Breakdown of circuit resistance and inductance

	R ($\mu\Omega$)	L (nH)
HPG & output bus	11.66	186
ITD busbar & switch	6.34	154
TF coil	3.00	120
Total	21.00	460

BUSBAR LEADS

The portion of each busbar which descends into the cryostat is composed of six pairs of discrete L-shaped bus leads. Each pair of bus leads is clamped into the terminals of a TF plate by a non-ferrous nickel alloy (Inconel™ 718) clamp. Electrical insulation between the clamp and the conductor is provided by ceramic spacers located above and below the terminal conductors and an insulative film on the sides of the joint. The ceramic spacers also compensate the thermal expansion mismatch between the terminal clamp

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Figure 3. Five of six ITD busbar/switch assemblies

Figure 4. Busbar leads (outer and inner)

and the conductors. Steel wedge jacks located between the clamp and the ceramic spacers supply the preload pressure necessary to ensure good electrical contact in the joint. The L-shaped bus lead pairs (inner and outer), as originally constructed, were machined from 7075-T6 aluminum (fig. 4). To each 60° sector of the TF coil, six pairs of the leads were connected and were reinforced using an A-36 carbon steel plate with a G-10 fiberglass-epoxy insulator.

A mechanical failure of the outer leads occurred during a 7.2 MA experiment. Current and voltage profiles during the test were nominal up to the point (1.10 MA/HPG, 14.7 T toroidal field) when the 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. Two-thirds of the failures occurred in the finger joint region of the outer aluminum lead near the terminal clamp. The other third of the failures occurred along a threaded hole in the outer lead. All of the inside leads were intact after the failure.

An interesting aspect of the failure was that the current level per generator at the time of failure was actually lower than the previous test (1.13 MA/HPG at 15.0 T). An additional detail about the test is that the switch contacts of one of the busbars showed severe arc damage and the

Figure 5. Stress contours in the original busbar leads during a 15 T ITD experiment

expendable contact ring broke and was dislodged. As learned later, a current distribution problem did exist in the explosive switch design and could have caused the switch failure. It is now well known from detailed analysis that the leads were underdesigned, but one possible explanation for the failure occurring at a lower current level than the previous test would be the unbalanced loading from a closing switch failure.

Material testing at LN₂ temperature revealed the expected tensile yield strengths of 827 MPa (120 ksi) in the steel and 586 MPa (85 ksi) in the aluminum. LN₂ tensile elongations were 12% for the steel and 4% for the aluminum. The aluminum leads showed some degree of plastic deformation while the steel backup plates exhibited brittle fracture, suggesting the steel was loaded at a strain rate comparable to an impact.

A detailed study of the lead region was initiated, starting with a two-dimensional (2-D) FEA as shown in figure 5. Thermal, electromagnetic, and combined analyses were performed. The thermal analysis showed that upon cooling, the bus leads and the backup plate would pull away from each other due to mismatching thermal contractions. This separation significantly reduced the expected level of reinforcement from the steel plate. The problem was compounded by the stress concentration created by the threaded hole used to couple the leads to the backing steel. The combined analysis revealed stresses in the failed area of the aluminum leads which compare closely to the yield strength of the material.

At this point, a new lead design began to evolve, eliminating these weaknesses. Given the high strain rate of the experiment and the observation of brittle failures, the change to a tougher material was made. At a sacrifice in cost and machinability, beryllium copper, identical to that used for the TF coil, was selected for its superior toughness, strength, and conductivity at LN₂ temperature. Incorporated in the new design were several new features:

- use of beryllium copper (Brush Wellman—Alloy #3 HT) (689 MPa (100 psi) yield strength, 64% IACS conductivity increasing by a factor of 2.3 at LN₂ temperature)
- eliminate stress concentration (threaded hole)
- eliminate backup steel plate which creates thermal stresses and complicates stress analysis
- increase in conductor area at both ends of the lead
- increase in radius at the right angle bend of the lead
- busbar coax shifted radially outward to accommodate thicker leads and larger radius
- use of Inconel (nonmagnetic, tough at LN₂ temperature) bolts and backing plates at upper lead joint.

Figure 6. Stress contours in redesigned beryllium copper busbar lead during a 20 T ITD experiment

Figure 7. Sectional view of the ITD coaxial closing switch

With the above mentioned design modifications, a three dimensional FEA model was constructed of the outermost busbar lead (fig. 6). The 3-D model revealed an additional high bending stress in the reduced cross section region near the Inconel clamped joint. This stress is the result of magnetic separation forces acting on the angled section of the lead. The original lead design had 1.5 mm (0.06 in.) gaps between adjacent leads with a G-10 shim filling the gaps. These gaps varied and the shim did not provide adequate assurance that loading could be transferred from lead-to-lead. To eliminate the bending stress and adequately support the leads against each other, the new design incorporates an epoxy filler that is pumped into the gaps after assembly.

HIGH-CURRENT, FAST-ACTING SWITCHING SYSTEM

Unlike the full scale IGNITEX experiment, the ITD requires fast-acting closing switches. The brushes of the Balcones HPGs were designed for current rise rates of about 10 MA/s, and could experience excessive localized heating if commutating directly to the ITD circuit, which has a rise rate of about 50 MA/s. With the use of switches, all of the pneumatically actuated brushes have time to seat on the rotor before current is conducted. An added benefit is the reduction of unbalanced loading which might take place due to imprecise timing between the circuits. While the interval of time between the firing signal and switch closure is about 100 μ s, the timing consistency between switches is on the order of 10 μ s.

The design of these switches is a scaled up version of a design which has evolved and proven itself over the past 5 years [8]. The coaxial switch is integrated into a coaxial-to-flat plate transition in each busbar (fig. 7). It operates when explosive cord propels an expendable copper "throw ring." The 20 cm (8 in.) diameter throw ring lodges into an annular gap between two reusable chromium copper "catch rings," transferring current to the TF coil. Magnetic force assists in lodging and holding the throw ring in the taper, assuring good electrical contact.

As testing levels increased to over 1.0 MA per switch, two problems arose in the switches. One was an increasing appearance of melt spots on the throw ring and adjacent catch ring contact surfaces. The spots, presumably due to current constriction, generally appeared on the top half of the switch. Based on the locations of the melt spots, a hypothesis was made that current flow was constricted circumferentially to the upper half of the switch due to a restriction in conductive area. The second problem was an occasional dislocation, in varying degrees of severity, of a throw ring from its closed, seated position. This was characterized by more severe thermal damage to the con-

tact surfaces, although no change in circuit impedance was discernable from the test data. It was considered possible that the same circumferential current constriction was causing an electromagnetic imbalance sufficient to dislodge the throw ring.

In an effort to direct current flow into the sides and lower half of the switch, a diverting insulator was installed at the top, and a copper distribution ring was added in series with the catch rings. These modifications eliminated both problems. To date, the switches have successfully carried pulses of up to 1.356 MA with an action of 1.0×10^{11} A²s and no melting of contacts.

CONCLUSION

The development of a high current, low impedance transmission system for a 20 T prototype tokamak has proven challenging but achievable. The mechanical failure of the original design led to the redesign of the busbar leads which connect to the TF coil. Two and three dimensional FEA aided in the identification of excessive stresses and the successful reduction of those stresses in the new design. The system, consisting of six parallel identical busbars, has transferred a peak current of 8.14 MA to the experimental magnet.

Melt spots and occasional dislodging of switch throw rings led to the diagnosis of improper current distribution attributable to a conductor area restriction. These problems were alleviated by the addition of a current diverting insulator and a copper distribution ring.

Experimental progress of the ITD for year 1991 is charted in table 1. The reported improvements to the transmission system allowed the ITD to operate at a level which is 82% of the program goal. The achievement of an on-axis toroidal field of 20 T is expected to occur soon after the reestablishment of funding.

ACKNOWLEDGMENTS

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REFERENCES

1. M.D. Werst et al., "Design of a Prototype 20 Tesla, Single Turn, Toroidal Field Coil for the Fusion Ignition Experiment (IGNITEX)," 13th Symposium on Fusion Engineering, Knoxville, TN, October 1989.
2. K.T. Hsieh et al., "Electromechanical Analysis of a Prototype 20 Tesla, Single Turn Toroidal Field Coil for IGNITEX," 13th Symposium on Fusion Engineering, Knoxville, TN, October 1989.
3. M.N. Rosenbluth, W.F. Weldon and H.H. Woodson, "Basic Design Report of the Fusion Ignition Experiment (IGNITEX)," presented in *Texas Atomic Energy Foundation Project Progress Report*, March, 1987.
4. M.D. Werst et al., "Magnet Technology Demonstration For an Ignition Single Turn Tokamak," 9th Topical Meeting on the Technology of Fusion Energy, Fusion Technology TM ISSN: 0748-1896, Oak Brook, IL, Oct. 7-11, 1990.
5. J.H. Gully, "HPG Operating Experience at CEM-UT," *IEEE Transactions on Magnetics*, Volume Mag-22 No. 6, Nov. 1986.
6. J.R. Kitzmiller, "Testing the 60 MJ Pulsed Homopolar Power Supply at The University of Texas Center for Electromechanics," 7th IEEE Pulsed Power Conference, Monterey, CA, June 1989.
7. G.W. Brunson et al., "Development of Preloading and Precooling Systems for a Single-Turn Ignition Tokamak," 9th ANS Topical Meeting on the Technology of Fusion Energy, Oak Brook, IL, October 7-11, 1990.
8. R.L. Sledge, J.H. Hahne, "Experimental Data on High Power Explosive Opening and Closing Switches at CEM-UT," 7th IEEE Pulsed Power Conference, Monterey, CA, June 1989.