**HIGH-CURRENT BUSBARS FOR A PROTOTYPE
HOMOPOLAR-TOROIDAL MAGNET SYSTEM
FOR FUSION IGNITION**

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ABSTRACT

The Ignition Technology Demonstration (ITD) is a full torus, scaled prototype of the 20 T toroidal field (TF) coil of the proposed fusion ignition experiment IGNITEX. The 0.06 scale in linear dimension is based on the linear relation between the peak current of an existing power supply (9 MA) and the current required to produce a 20 T field in the full-scale machine (150 MA). Presented here are the design and performance of a busbar and switch which have successfully transferred a total current of 6.75 MA to the ITD during a 15 T experiment. Design considerations included thermal and electromechanical stresses, material properties in liquid nitrogen, electrical resistance and inductance, and physical integration with the existing power supply. The ITD is driven by a 60 MJ, 9 MA power supply consisting of six 1.5 MA homopolar generators (HPGs) located in the Center for Electromechanics at The University of Texas at Austin (CEM-UT).

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. 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, with low cost, a 20 T TF coil using an existing HPG power supply. Reported in this paper is one major task of this program: providing a busbar and switch system which is capable of delivering a 9 MA current pulse with a duration of about 100 ms. The program has been fortunate in drawing upon years of experience in the design and operation of megampere systems at CEM-UT.^{1,2}

HIGH-CURRENT BUSBAR DESIGN AND OPERATION

Mechanical Design

The six drum-type HPGs, each rated at 1.5 MA at 100 V, are located in a hexagonal pit along with riser busbars which carry current to several floor level experiments. The inductance and resistance of the riser busbars and the lack of floor level space for the experiment dictated locating the ITD below floor level, centered in the hex pit between the HPGs (Fig. 1). This simplified design of the liquid nitrogen (LN₂) cryostat, allowing the six identical busbars to extend down from the HPGs into the open tub cryostat and eliminating the need for cryogenic seals. However, the tasks of bus design, assembly, and testing were complicated by the limited connection options and confined space.

ITD Magnet Operating Parameters

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

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

A substantial effort was involved in the design and installation of busbar connection tabs to the existing system. A scale model of two connection options was built and tested to predicted peak values of electrical action and current using an HPG and a bank of capacitors, respectively. One of the options was selected on the basis of produced temperatures and mechanical strains, which were monitored during the 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.

The busbar design (Fig. 2) consists of two flat plate configurations on each side of a 23 cm (9 in.) outer diameter coaxial bus. A coaxial explosive closing switch is integrated into the first transition. Mica band heaters on the inner and outer coaxes prevent condensation from forming in the switches and HPGs.³ A finite element analysis (with the numerical code ABAQUS⁴) of the busbar

Figure 2. Sectional view of ITD busbar with current path

assembly was performed to calculate thermomechanical forces during cooling. The analysis modeled the busbar assembly as beam elements attached end to end. 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 alloy was chosen for the major busbar components based on its good mechanical strength, electrical conductivity, weldability, and machinability.

The portion of each busbar which descends into the cryostat is composed of an A-36 carbon steel plate and G-10 composite insulator which reinforce six pairs of discrete 7075-T6 aluminum alloy bus leads. Each pair of bus leads is clamped into the terminals of a TF plate by a nonferrous nickel alloy (InconelTM 718) clamp (Fig. 3). Electrical insulation between the clamp and the conductor is provided by ceramic spacers located above and below the terminal conductors and 0.005 in. MylarTM film on the sides of the joint. The custom ceramic spacers are primarily used to compensate the thermal expansion mismatch between the terminal clamp and the conductors. AISI 4340 steel, wedge jacks, located between the clamp and the ceramic spacers, supply the preload pressure necessary to ensure good electrical contact in the joint.

In designing the terminal connection fingers of the TF plate and leads, the distribution of current was analyzed. Given the limited volume available for the terminals and the subsequently high current densities, localized heating was of concern. Current distributions were compared for various finger geometries. The analysis produced terminal proportions for optimal current distribution (Fig. 4). Maximum temperature rise was determined to be 145 K, a tolerable increase for the leads which are initially at 77 K.

Figure 3. Connection of TF coil terminals to busbar leads

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Figure 4. TF terminal current contour

Bolted contacts were analyzed for Joule heating and clamping pressure. Bolt torques were calculated, including effects of thermal shrinkage, material stiffness, and contact pressure. Contact pressures of at least 21 MPa (3,000 psi) are designed into each interface, overcoming small, discrete point contacts. Several aluminum-to-aluminum joints are copper plated while others are assembled with copper shims. Unplated aluminum surfaces are treated with electrical joint compound to break up resistive oxide coating. Preliminary assemblies of the buswork and ITD experiment are shown in Figures 5 and 6.

Electrical Design

Conceptual design of the busbar had the following requirements: each busbar must simultaneously deliver a peak current of 1.5 MA with a pulse width on the order of 100 ms and an action of about $1.12 \times 10^{11} \text{ A}^2\text{-s}$ into a 60° sector of the LN₂ cooled TF coil. Given the fixed circuit parameters of the TF coil and HPGs, inductance and resistance criteria were calculated and factored into the final design. It was not feasible to create the flat-top pulse shape characteristic of the actively controlled IGNITEX, but it was possible to create a current contour which would produce stresses representative of those in the full-scale TF magnet.⁵ Inductance must remain low in order to minimize pulse width, while resistance must 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". Ringing is undesirable for these particular HPGs because of possible HPG brush gear dam-

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Figure 5. Five of six ITD busbar/switch assemblies

age through rotor reversal, although small reversals are considered tolerable for the brush gear.

Testing

The circuit as built was found to be slightly underdamped. The predicted rotor reversal during a 20 T experiment is approximately 100 rpm, a safe level for the HPG brushes. Predicted pulse width at that level 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 a resistive-inductive-capacitive circuit simulation.⁶ A breakdown of the average values are given in Table 1.

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Figure 6. Completed Ignition Technology Demonstration assembly

Table 1. Breakdown of circuit resistance and inductance per 60° sector

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

Low current, room temperature tests up to 11 T have been performed. For the medium current phase of testing, the cryostat, hydraulic press base plate, heating system, and support structure were installed. LN₂ cooled tests up to 15 T have been successfully performed without assistance from the press. A peak current of 1.12 MA per busbar was reached. Current and voltage waveforms from the 15-T test are shown in Figure 7.

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Figure 7. HPG current and voltage data from a 15 T ITD experiment

A mechanical failure of the leads which clamp to the TF coil occurred during a 7.2 MA experiment utilizing the hydraulic press. Current and voltage profiles during the test were nominal up to the point (1.15 MA/HPG, 15.3 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; the magnet realized no damage. Material testing at LN₂ temperature confirmed 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 more detailed study of this region was initiated, starting with a two-dimensional finite element analysis (ABAQUS) as shown in Figure 8. Thermal, electromagnetic, and combination analyses at 7.0 MA 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 combined analysis revealed stresses in a fractured area of the leads, which compared closely to the yield strength of the material, suggesting that the incremental current for this test was enough to cause failure. The problem was compounded by the stress concentration created by a threaded hole used to couple the leads to the backing steel. The redesign

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Figure 8. Stress contours in busbar leads during a 15 T ITD experiment

presently underway will eliminate the threaded hole and steel backup plate in lieu of a thicker monolithic bus lead which can be modeled more accurately.

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 over 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 five years at CEM-UT.⁷

The coaxial switch (Fig. 9) is integrated into a coaxial/flat plate transition in each busbar. The switch 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. Contact pressure of 69 MPa (10,000 psi) is calculated for a 20 T experiment. To date, the switches have successfully carried pulses of 1.15 MA and 6.0×10^{10} A²-s. Based on the contact area of the throw ring surface (2,452 mm²), a specific action of 1.0×10^4 A²-s/mm⁴ was realized without melting of the contacts. This compares to a published action constant of 8.0×10^4 A²-s/mm⁴ for copper melt beginning.⁸

Six firing boxes, containing commercially available firing modules and featuring fiber optic coupling to the power supply controller, simultaneously trigger the switches. The explosive ring in each switch is normally initiated by four detonators, although the detonator lines are staggered such that one firing box fires two detonators on two adjacent switches, as shown in Figure 10. In the case of a no-fire from one of the boxes, the explosives in a switch will propagate fully from the other two detonators. In this instance, the switch will operate at an acceptable speed for the ITD experiment, albeit with a closure time which is (on the order of 10 μ s) longer.

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Figure 9. Sectional view of the ITD coaxial closing switch

Figure 10. Arrangement of switch detonator firing cables

CONCLUSION

A high-current, high-action busbar and switch system has been designed, built, and operated. The production of 2.0, 8.0, 12.0, and 15.0 T magnetic fields in a toroidal configuration was realized within a six day period. This set of pulses demonstrated a peak system current of 6.75 MA. In the next phase of ITD testing (scheduled to begin later this year), discharges of 9 MA will demonstrate the production of 20-T fields in a toroidal configuration.

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REFERENCES

1. J.H. GULLY, et al., "HPG Operating Experience at CEM-UT," *IEEE Transactions on Magnetics*, Vol. Mag-22, No. 6, November, 1986.
2. J.R. KITZMILLER, et al., "Testing the 60 MJ Pulsed Homopolar Power Supply at The University of Texas Center for Electromechanics," 7th IEEE Pulsed Power Conference, Monterrey, CA, June 1989.
3. 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, 1990.
4. ABAQUS: A commercial general purpose finite element program on solid mechanics, developed by Hibbit, Karlsson, and Sorenson, Inc.
5. 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.
6. 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.
7. R.L. SLEDGE and J.H. HAHNE, "Experimental Data on High Power Explosive Opening and Closing Switches at CEM-UT," 7th IEEE Pulsed Power Conference, Monterrey, CA, June 1989.
8. T.J. TUCKER and R.P. TOTH, "EBW1: A Computer Code for the Prediction of the Behavior of Electrical Circuits Containing Exploding Wire Elements," U.S. Energy Research and Development Administration Project No. AT (29-1)-789, April, 1975, Sandia Laboratories, SAND-75-0041.