# DIAGNOSTIC SYSTEM FOR A 20 TESLA, TOROIDAL, SINGLE TURN MAGNET PROTOTYPE FOR FUSION IGNITION

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Original

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## ABSTRACT

The Center for Electromechanics has designed, fabricated, and is now operating a prototype of a full torus, 20 Tesla (T) on-axis, single turn, toroidal field (TF) magnet system powered by the Balcones Homopolar Generators (HPGs). This magnet system is part of the Ignition Technology Demonstration (ITD) program for the fusion ignition experiment (IGNITEX). The six HPGs connected to the prototype magnet in parallel are capable of producing a 9 MA, 150 ms, current pulse required for a 20 T ITD test. The diagnostic system for the prototype magnet is designed to determine strains, temperatures, and magnetic fields at several locations in the TF magnet. These values are used to verify numerical predictions by electromechanical and thermomechanical analyses. Operating conditions for the instrumentation inside the cryogenically cooled magnet are extreme; localized temperatures inside the magnet can rise from -196°C to 200°C during the current pulse and the magnet field levels near the inner leg surface can rise to 30 T in 30 ms. The specifications, testing, and layout of the diagnostic and data acquisition systems for the ITD prototype are presented in this paper.

## INTRODUCTION

The IGNITEX experiment has been proposed as a means to produce and control ignited plasmas in a relatively simple and inexpensive manner.[1] This experiment was based upon a compact high field tokamak design that would be capable of attaining and controlling fusion ignition using only ohmic heating. Due to the difficulty and expense of attaining 20 T fields using conventional, multiturn, toroidal magnet systems, a unique single turn TF magnet powered by HPGs is used in the IGNITEX design.[2] To demonstrate the feasibility of the TF magnet system proposed for the IGNITEX design, the ITD program has been undertaken. To date, the prototype TF magnet has produced a purely toroidal, on-axis field of 15.0 T.

For the ITD program, a 0.06 scale prototype of the TF system has been built and is currently being tested. The experiment uses a single-turn TF magnet and is powered by six HPGs connected in parallel. The TF magnet is constructed from high-strength beryllium copper alloy plates and is axially and radially preloaded to decrease peak stress levels during operation. To increase the time the TF coil can operate at peak fields without excessively high temperatures, the magnet is precooled to -196°C with liquid nitrogen ($LN_2$).[3] The HPG system used in the ITD program is the 60 MJ, 9 MA Balcones HPG power supply located at the Center for Electromechanics at The University of Texas at Austin (CEM-UT).[4] The ITD program objective is to simulate stresses, temperatures, and magnetic fields which will be developed in the full-size IGNITEX TF magnet. Because of the lack of previous experiments in predicting the performance of single turn TF coils, an extensive diagnostic system has been installed and used to verify the analytical models and computer codes used for the design of both the ITD and IGNITEX.

This paper describes the diagnostic system used in the ITD program. The desired measurement parameters, operating environments, and the selected sensor components which are used in the experiment are discussed. Results from ITD tests are compared to the values predicted by electromechanical and thermomechanical analyses. The design of the TF magnet instrumentation and data acquisition system requirements are covered. Future improvements in the TF magnet diagnostic system are described.

## REQUIREMENTS FOR THE ITD DIAGNOSTIC SYSTEM

Operating conditions for the instrumentation installed inside the TF magnet are extreme. Electromechanical and thermomechanical numerical simulations have shown that the 0.06 scale TF magnet will have the highest thermal, magnetic field, and strain changes near the inner leg of the magnet. The average temperature of the entire magnet during a full 9 MA, discharge of the HPGs rises from -196°C to -150°C. However, localized areas of the inner leg of the magnet rise from -196°C to approximately 200°C. The peak magnetic field on-axis is 20 T however, at the surface of the inner leg the fields rise to a peak of 30 T in 30 ms. The strains in the inner leg rise to over 0.5% strain. Sensors located in other positions on the TF magnet would experience less thermal, magnetic field strain changes but, all must be cryogenically rated.

The measurements that are required to validate the proper operation of the ITD prototype are magnetic field, current, temperature, strain, and hydraulic pressure (preload structure). The magnitude of localized magnetic field throughout the TF magnet is needed to map the field distribution and determine the field uniformity. Currents and voltages that are developed from each of the six HPGs are used to assess TF magnet performance, potential magnetic field ripple, and potential generator-to-generator current imbalances. Localized temperature measurements are important in verifying the current distribution in the TF magnet. In addition, these measurements also determine the material properties and temperature gradient induced stresses in the TF magnet. Hoop and axial strain measurements are needed to calculate and compare, to analytical models, to determine the level of induced stress, fatigue life, uniformity of the axial preload, and the bucking and wedging forces.

The TF magnet experiment is located below floor level at the base of the CEM-UT, HPG pit. The location of the ITD with respect to the HPGs and bus connections can be seen in Figure 1. This minimizes the interference of TF coil testing with other experiments that also use the HPGs and reduces the length and electrical characteristics of the TF magnet busbars. The existing geometry of the HPG pit determined that the TF magnet be positioned below the HPGs and this provided a way of pool cooling the TF magnet in an open-top cryostat. The cryostat design allows better access to inspect the magnet between tests and eliminates the need for cryogenic seals on the busbars and TF magnet instrumentation leads. Access to the ITD experiment is limited and instrument data must be transmitted from the HPG pit to data acquisition and real time display systems in the HPG control room. This requires sensors or methods capable of sending diagnostic data for over 25 m while minimizing the potential environmental and long lead affects.

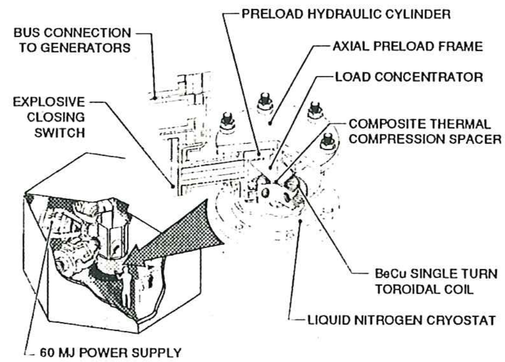


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Figure 1. IGNITEX technology demonstrator (ITD)

## ITD DIAGNOSTIC SYSTEM LAYOUT

The magnet is powered by six HPGs, and therefore each HPG provides current for only a 60° sector of the TF coil. The 60° division is also used as the basis of the TF coil instrumentation layout and designated as sectors I through VI. Each sector is made of six 10° wedge shaped plates and designated as plates 1 through 6. Angular displacements on-axis of the TF magnet starting at inner leg are labelled a A through F with G being designated as the Inconel™ clamp position. The Inconel™ clamp holds the terminal buswork to the TF magnet and supports some of the magnet's axial loading. These explanations of the positions of the TF magnet instrumentation are illustrated in Figure 2. A list of the ITD sensor components is given in Table 1. The total number and location of the instrumentation used in the ITD TF magnet diagnostic system are listed in Figure 3.

Table 1. ITD dianostic system sensor components

| REQUIRED MEASUREMENT | RANGE | SENSOR TYPE |
|---|---|---|
| magnetic field | 0 to 30 Tesla | Hall-effect probe |
| current | 0 to 9 MA | Rogowski coil |
| temperature | -196°C to +200°C | thermocouple |
| hydraulic pressure | 0 to 10,000 psi | thin-film pressure transducer |
| strain | 0 to 5,000 $\mu\epsilon$ | resistance and fiber-optic interferometry strain gages |

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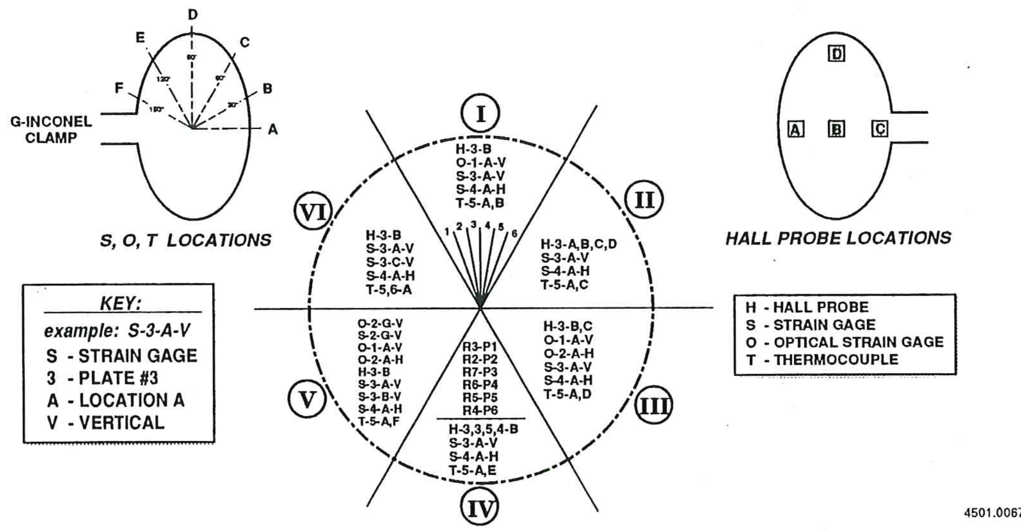


Figure 2. TF coil instrumentation layout

***12*** **Hall probes inside TF coil**

***6*** **Rogowski coils**
- **6 HPG bus current**

***24*** **thermocouples**
- **12 inside TF magnet**
- **12 bus-mounted**

***1*** **pressure transducer on preload frame hydraulic system**

***21*** **strain gages**
- **15 resistive gages on TF magnet**
- **6 optical interferometric gages on TF magnet**

4501.0069

Figure 3. Total ITD diagnostic system

## MAGNETIC FIELD DIAGNOSTIC SYSTEM

Magnetic fields inside the 0.06 scale prototype, are measured with F. W. Bell BHT-921 Hall Generators. These Hall-effect probes are of small size, have good temperature stability, and are rated for cryogenic use. Because the BHT-921 is not supplied calibrated above 3 T, the probes used in the ITD were calibrated at the MIT, National Magnet Laboratory using a cylindrical, 5 cm bore, 20 T, bitter magnet. The Hall probes are mounted in G-10 fixtures and mechanically held in position by the ceramic outer-leg insulators. This mounting arrangement prevents the sensors from being strained and damaged during TF magnet operation however, it does not allow for positioning better than approximately 1.5 mm. Shown in Figure 4 are typical, sector, on-axis Hall probe results from ITD test #9, $LN_2$ cooled and 15 T field on-axis. The field variations in Figure 4 are believed to be due to a mounting positioning error in the radial direction. During the next phase of magnet testing, a more accurate method of positioning the Hall probes will be used.

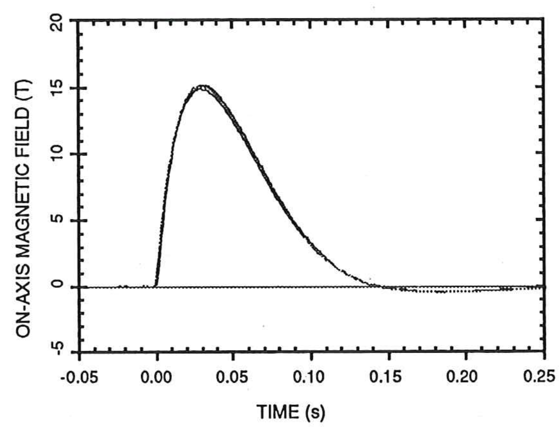


Figure 4. On-axis Hall probe results from ITD test #9

## CURRENT AND VOLTAGE MEASUREMENT DIAGNOSTICS SYSTEM

The circuit design of the ITD system allows the current to be measured away from the cryogenic temperatures, high magnetic fields, and high stress levels. The current measurement sensors used are the existing custom-made and calibrated, individual, HPG current Rogowski coils with passive integrators. Because Rogowski coils with passive integrators often have a five percent variation in calibration, the recorded currents may also vary. The voltage output from the six HPGs was taken by the voltage instrumentation brushes mounted inside each HPG. The recorded individual HPG currents and voltage outputs from test #9 are shown in Figure 5. Any potential variation in current or voltage can be easily corrected by changing the individual HPG field current which will change the HPG output voltage and current.

## TEMPERATURE MEASUREMENT DIAGNOSTIC SYSTEM

Localized temperatures on the inner leg of the TF coil were predicted to rise from -196°C to 200°C for a 20 T test. This type of measurement requires a sensor with fast thermal response. The sensor also has to be of small size, resistant to magnetic and inductive effects, and be strain resistant if surface mounted. The temperature sensor that meets the ITD requirements are type T thermocouples made from 30 AWG wire. These thermocouples were made very small and flat for minimum noise and fast response. The thermocouples are encapsulated in 1 mil Kapton® film for electrical isolation and glued to the inside surface of the TF magnet with M-Bond 600® adhesive. The results from the tests have showed lower than predicted temperature levels but the time to maximum temperature took longer than expected. The thermocouple results for test #9 are shown in Figure 6. The differences between actual and predicted results due to the analytical peak nodal temperatures inside the magnet conductor compared to a surface area measurement with the thermocouples. The position and the use of adhesives also affects the measurements.

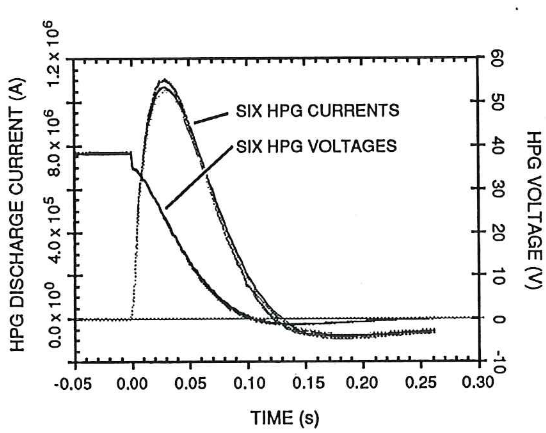


Figure 5. HPG currents and voltage outputs from test #9

## HYDRAULIC PRESSURE DIAGNOSTIC SYSTEM

Static and dynamic measurement of the hydraulic pressure in the axial preload structure is necessary to determine the level of force being applied and the axial displacement during a discharge. The hydraulic system is external to the TF coil/cryostat, and is protected from significant thermal and magnetic affects. An Omega® Series PX612 pressure transducer was selected. This pressure transducer has a low drift, a relatively fast response time of 1 ms, and is internally temperature compensated. The calibration of this transducer was checked with a Ronan calibrator and installed on the hydraulic preload structure. This diagnostic will be extremely valuable when the high level current tests are performed later this year.

## STRAIN MEASUREMENT DIAGNOSTIC SYSTEM

Two types of strain gauges are used in the ITD program because the extremely harsh environment inside the TF magnet. The strain gauges must be resistant to thermal, magnetic, inductive, and strain effects. One of the gauges selected is a Micro Measurements® WK-09-062AP-350 resistance strain gauge. These gauges have a large allowable temperature range (-269°C to 290°C) and strain range (to 1.5%). Again, these sensors were bonded to TF magnet components with M-Bond 600®. The small size of the gauges and the use of

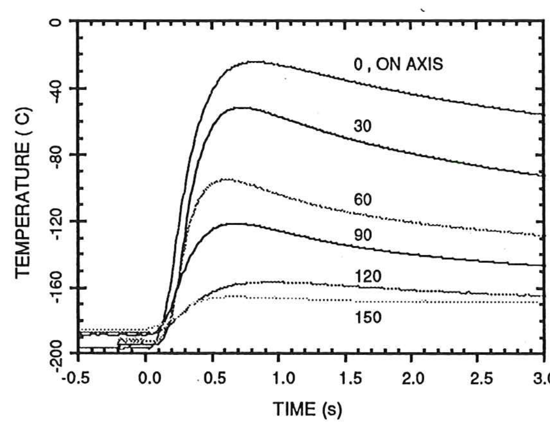


Figure. 6. Thermocouple results for test #9

transposed leadwires was partially successful in minimizing inductive voltage noise during a current discharge. Some of the gauges installed have showed predicted levels of strain while other gauges have showed inductive pickup. Results from a properly working but slightly noisy resistance strain gauge can be seen in Figure 7 for tests #2 to #5. A test using only the preload structure to apply forces to the TF magnet showed predicted strain levels from all working gauges and confirmed the uniformity of the axial preload.

## OPTICAL STRAIN GAUGE DEVELOPMENT

In anticipation of the problems associated with resistive gauges in the TF magnet environment, a second type of strain gauge has been developed, installed, and tested in the TF magnet. This novel strain gauge is based on a Michelson Interferometer, and uses single-mode, optical fiber technology.[6] Equal length interferometer paths are positioned close together to improve sensor ruggedness while minimizing environmental signal noise and alignment problems.

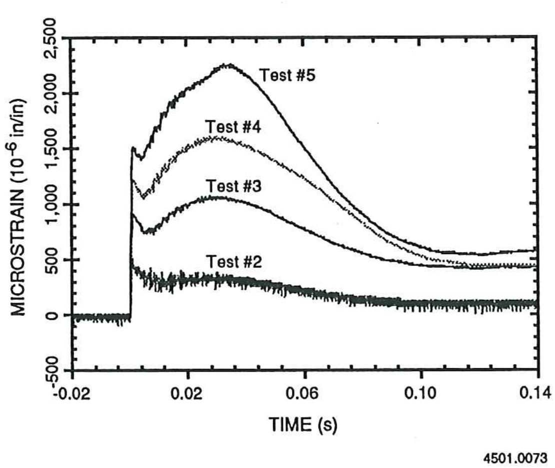


Figure 7. Resistance strain gauges for tests #2 to #5

A fiber optic Michelson Interferometer, see Figure 8, operates on the principle of constructive and destructive interference of coherent light. When coherent light enters a 3dB directional coupler, half of the light propagates down the reference path and the other half down the sensor path. The light then reflects off the mirrored fiber path ends and returns to the directional coupler to recombine as the interfered output. As the sensor path changes length by one-half wavelength of light ($\lambda/2$), compared to the length of the reference path, the interfered light intensity output changes by a sinusoidal $2\pi$ phase shift.

For use as a strain gauge, part of the sensor path is bonded to the TF magnet surface with Emerson Cuming epoxy.[6] Strain in the TF magnet changes the length of the sensor path compared to the reference path length causing a light intensity phase change in the output.[7] ITD test results have shown that this strain sensor is accurate at lower current levels but at higher current levels (15 T) the sensor is progressively affected by thermal and vibration noise resulting in higher than expected strain results. The single-mode glass fibers used in the strain sensor are very strong in tension but proved to be more fragile than the standard copper wires used for other electronic sensors during handling and installation of the TF magnet.

## TF MAGNET DATA TRANSMISSION AND ACQUISITION SYSTEMS

Due to the limited access to the TF magnet experiment, all required sensor information is

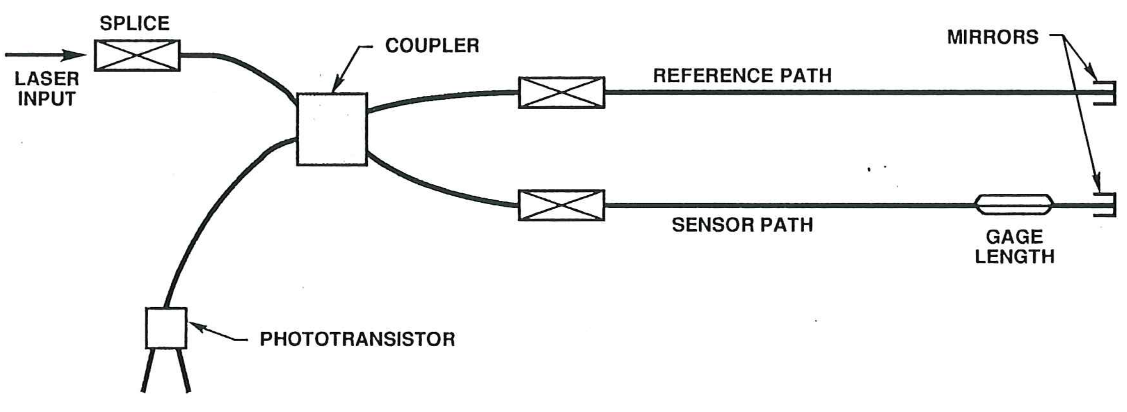


Figure 8. Fiber optic Michelson interferometer

transmitted from the HPG pit to data acquisition and real time display systems in the screen room. This required sensors or methods that would send diagnostic data for over 25 m while minimizing the potential environmental and long lead affects. The Rogowski coils used in the HPGs system were already installed with the proper data lines to the screen room and required no addition modifications. However, to provide for the accurate transmission of data from the Hall probes, resistance strain gages, and thermocouples required the use of Analog Devices 3B Series modular signal conditioners. These modules are used to transmit the signals from the sensors to the screen room in the form of 4 to 20 mA current loops. Single-mode fiber optic cable is used from the screen room to the HPG pit for the transmission of light to and from the optical strain gauge. The design of the interferometry sensor system makes the optic signal carried by the cable resistant to environmental affects. In the screen room, the required data is recorded using digital oscilloscopes and VAX computer based digitizers. A symbolic overview of the TF magnet data system can be seen in Figure 9.

## CONCLUSION

A diagnostic system for a full-torus, 20 T, single-turn magnet prototype has been designed, installed and tested. The diagnostic system has provided the information necessary to verify many of the design features of the ITD TF magnet. The data collected has also provided valuable information about the ability of different types of instrumentation to operate in extreme environmental conditions.

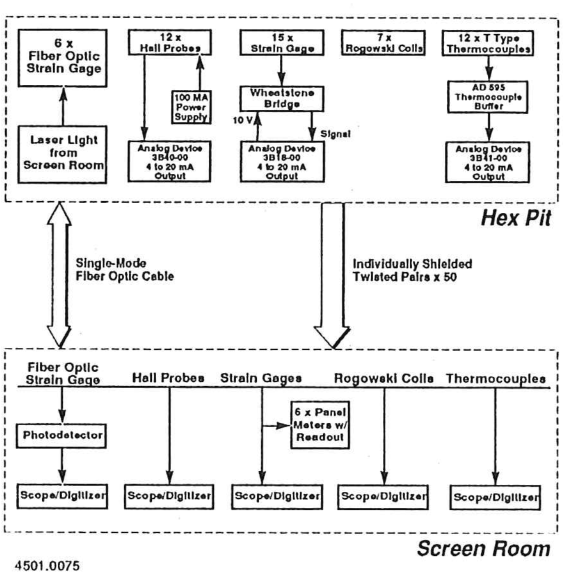


Figure 9. TF magnet instrumentation overview


## ACKNOWLEDGMENTS

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