GA–A23831

THERMAL ANALYSIS AND EXTENDED OPERATION SIMULATION OF THE DIII–D TF-COIL BELT BUS SYSTEM

by
M.E. FRIEND, P.M. ANDERSON, C.B. BAXI, and R.L. LEE

APRIL 2002

DISCLAIMER

GA–A23831

THERMAL ANALYSIS AND EXTENDED OPERATION SIMULATION OF THE DIII–D TF-COIL BELT BUS SYSTEM

by
M.E. FRIEND, P.M. ANDERSON, C.B. BAXI, and R.L. LEE

This is a preprint of a paper presented at the 19th IEEE/NPSS Symposium on Fusion Engineering, January 21–25, 2002 in Altantic City, New Jersey and to be published in the *Proceedings.*

Work supported by
the U.S. Department of Energy under
Contract No. DE-AC03-99ER54463

GA PROJECT 30033
APRIL 2002

Thermal Analysis and Extended Operation Simulation of the DIII–D TF-coil Belt Bus System

M.E. Friend, P.M. Anderson, C.B. Baxi, and R.L. Lee

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

Abstract—The DIII–D toroidal field [TF] belt bus system provides an electrical connection between adjacent TF-coil bundles to form a continuous current path for the TF-coil system. There is also a return path which is electrically isolated from the belt bus. The function of the system is to carry TF-coil current while minimizing the TF-coil error field in accordance with physics requirements. The system is currently capable of handling 5 s of operation with a peak current of 127 kA in the TF-coil. Future requirements for the system are the capability to support 10 s operation with 10 min cooldown periods in between shots. Experiments have been carried out which describe the physical parameters of the system, such as the contact resistance across the bus bar joints. Additionally, using an optical fiber-based temperature monitoring unit, the temperature response of the system to operations was determined. Based on these characterizations of the system, a 3-D thermal model was built to predict the behavior of the system for 10 s operations. The limitation of the system is the maximum allowable temperature of approximately 150°C for the G11 insulators. The model was constructed full scale per engineering drawings using Solidworks, meshed, and then exported to Cosmos for analysis. Once good correlation was achieved with the observed responses to 5 s pulses, the behavior of the system for 10 s pulses was predicted. Various design modifications, such as water cooled bolts, were simulated in order to estimate their impact on creating a system that meets the 10 s criteria.

I. INTRODUCTION

Previously, extrapolation from demonstrated plasma scaling laws lead to fusion power plant designs large in size and cost which required high magnetic fields and large plasma currents. Recent experiments at DIII–D and other tokamaks have identified new regimes of enhanced plasma operations called advanced tokamak (AT) operations [1]. These regimes have the potential to drive designs for smaller, cheaper steady state fusion power plants.

One of the primary goals of the DIII–D research program is to investigate these AT regimes and to demonstrate the ability to sustain AT plasmas for several relaxation times. In order to achieve these steady-state AT scenarios, DIII–D and its associated systems will have to be able to accommodate 10 s pulses with a minimum of 10 min cool-down period in between pulses. A few components of DIII–D will have to be upgraded in order to meet this criteria.

One system in particular that will require upgrading is the DIII–D TF-coil belt bus system. The function of the belt bus is to provide an electrical connection between adjacent TF-coil bundles and also to provide a return current path for the TF current. The interbundle connections and return bus are electrically isolated but interleaved in order to minimize the TF-coil error field. The system is shown in Fig. 1 and consists of upper and lower TF belt bus conductors which are connected, yet electrically isolated to the TF-coils. The electrical isolation is achieved by utilizing G11 spacers. Flexible copper straps on the outboard side provide the coil to coil toroidal connection yet allow for differential thermal expansion between adjacent coils. The return path is made via the inner flexible plates.

Currently, the TF-coil bus bar system is capable of handling 5 s of operation with a peak current of 127 kA in the TF-coil and a minimum of 10 min of cool-down in between shots. Active cooling is provided in the form of cooling pipes recessed in the TF-coils return bus bar (Fig. 1) as well as in the TF-coil. The cooling pipes for TF-coil return bus bar are currently connected with four cooling loops each consisting of twelve bus bars connected in series. The TF-coil cooling lines are connected in parallel.

This cooling arrangement unfortunately leads to relatively long conductive paths to both the inner and outer flexible straps. This inability to cool down the entire system leads to a ratchetting effect whereby there is a gradual increase in the maximum temperature of the system over the course of several shots/cool down periods until a steady-state condition is achieved. The primary thermal limitation of the system, however, lies in the maximum allowable temperature of 150°C for the G11 insulators.

II. EXPERIMENTAL CHARACTERIZATION

Utilizing an optical fiber based temperature monitoring unit [2], the temperature response of the TF-coil belt bus system was measured during tokamak operations. Since data

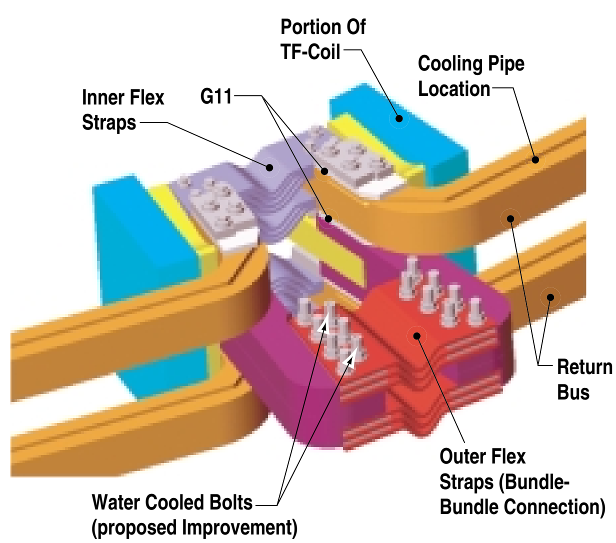

Fig. 1. CAD model of the TF-coil belt bus.

was collected during normal operations, systematic variations in TF-coil current were not carried out. $I_B^2 \cdot t$ values range from 0.16×10^{11} A^2 s for 50 kA power supply test shots to 1.36×10^{11} A^2 s for standard, full field 5 s shots. Likewise, cool-down times were also not systematically varied but range from 11 to 41 min. The results are plotted in Fig. 2 for a location on top of the outer flex strap (dash-dot curve). As can be seen by the data and discounting for the few cases of long cool down times and test shots, there is a general upward ratchetting of the observed temperatures over the course of the day. It is this set of experimental data that was used to validate the computer model.

III. COMPUTER MODELING

In order to develop a tool to enhance the thermal capabilities of the TF-coil belt bus, a 3-D computer analysis model was constructed. After minor modifications, verification with observed experimental data collected during operations was achieved. This allowed extrapolation to 10 s operations and examination of proposed design solutions to improve thermal performance to proceed with reasonable confidence.

Geometry for the model was constructed in Solidworks [3], a 3-D CAD solid modeling program. The components of the belt bus assembly were constructed per engineering drawings and to a high level of detail. Both left-right and up-down symmetry were assumed so as to minimize the numbers of nodes and elements in the meshed model (Fig. 3). Once complete, the model was then exported to Cosmos [4] for meshing and analysis.

Meshing of the model was completed utilizing a variable mesh density ranging from 0.01 to 0.005 m dependent on the thickness of the 47 individual parts in the assembly. In a few cases, parts were subdivided into subparts so as to more accurately model variations in volumetric heat generation as a function of variations in part cross sectional area. Due to the relatively small temperature differentials expected, material

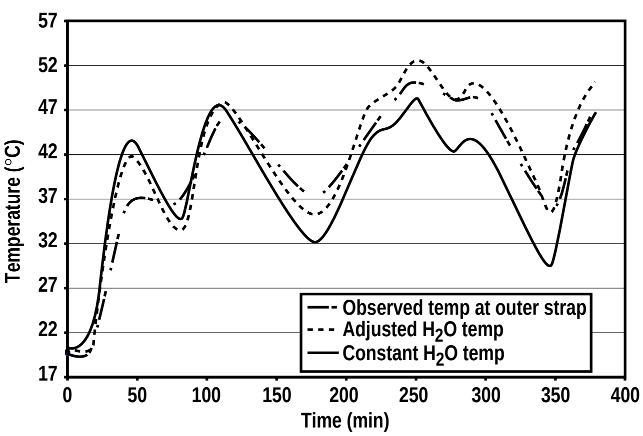

Fig. 2. Temperature just prior to a pulse for a location on the top of the outer flexible strap. The observed experimental data is compared with models for predicting the temperature of the system.

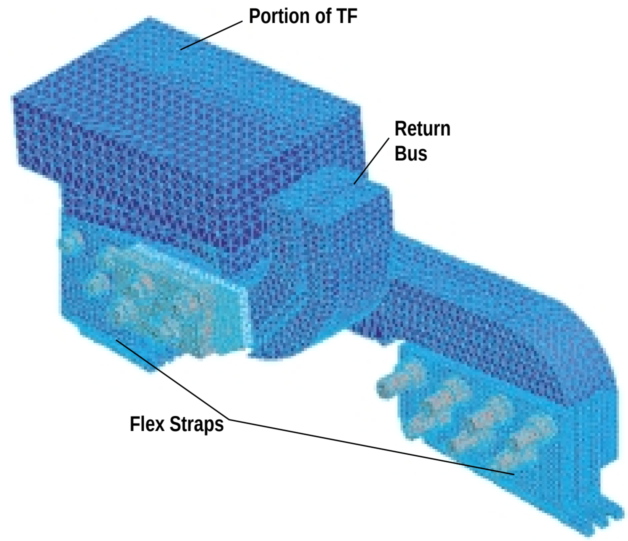

Fig. 3. The computer model once symmetry conditions have been applied and the model has been meshed. Mesh density was varied according to part geometry.

properties were assumed to be constant with the exception of the resistivity of copper which was defined as a function of temperature.

Heat generation was imposed on the model from two sources; by volumetric heat generation resulting from current passing through copper and by contact resistance resulting from current passing across a bolted joint. In both cases the heat generated is defined by the relationship $Q = I^2R$. To calculate volumetric heating, an equation can be derived by rewriting the resistance, R, in terms of resistivity, ρ, and dividing both sides of the equation by volume to yield the relation $q''' = (I/A)^2\rho$ where ρ is defined as a function of temperature, $\rho = 1.72 \times 10^{-08}\ [1 + (T–20) \times 0.003]\ \Omega m$, A is the cross sectional area perpendicular to the current direction and q''' is the rate of heat generation per unit volume. A simplified current distribution was assumed throughout the assembly. For example in the case of the return loop, I/2 (up/down symmetry) is assumed to flow down from the TF-coil and I/6 exits from each of the 3 outer flex straps. Though a square current pulse profile is assumed, the pulse length was adjusted such that the $I_B^2 \cdot t$ values agree with that in the experimental results. This simulates the total energy input into the system including ramp up and ramp down.

For heat generation as a function of contact resistance, the resistance is assumed as $2 \times 10^{-6}\ \Omega$. This assumption is based on data that was taken during thermo-mechanical tests for a bolted joint with 36 ft lb of torque [5]. Resistance data has also been collected on the return current loop, the inner flex strap, measured about 3 in along the bus bar. The averages for the lower and upper inner flex straps are plotted in Fig. 4 over the past ten years. Randomly selected toroidal locations for the upper and lower are also plotted for comparison. Following a tightening of the entire system in 1989, the average measured resistance is approximately $2.5 \times 10^{-6}\ \Omega$. This value, however, is not just the contact resistance. The

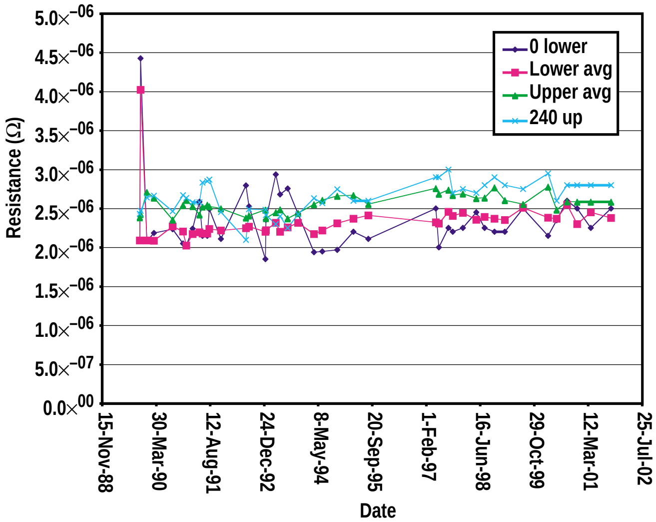

Fig. 4. Measured resistance across the inner flex strap is a function of date. The average values for the upper and lower inner flex straps are plotted along with values from randomly chosen, individual locations for the upper and lower inner flex straps.

resistance of the flex straps and 3 in of bus bar on either side of the flex straps are also included in the value. Assuming a circuit with 3 in of bus bar on either side of two straps in parallel, having each strap consist of $R_{contact} + R_{strap} + R_{contact}$ and then assuming that the contact resistances are equal yields the expression, $R_{measured} = R_{contact} + R_{strap}/2 + R_{bus\ bar}$. Using a resistivity per unit length for copper of 1.72×10^{-8} reduces the relation to $R_{measured} = R_{contact} + 1.0\times10^{-6}\ \Omega$. Thus, deducing the contact resistance from the measured resistance yields an average value of $1.5\times10^{-6}\ \Omega$.

Cooling in the model is achieved through water convective cooling at two locations; in the TF-coil and via a pipe imbedded in surface of the TF-coil return bus bar. A convective film coefficient of 5000 W/m^{2}K with a bulk temperature of 293 K was assumed. A boundary condition of zero heat flux was applied at all symmetrical boundary locations.

A simplified schematic of the system is provided in Fig. 5. As can be seen in the figure, the temperature of the G11 is a function of two thermally and electrically isolated circuits. The first of these is the TF-coil to TF-coil circuit which are connected via the outer flex strap. The second is the TF-coil return bus bars which are connected via the inner flex strap.

IV. RESULTS

The computer model was first run with data from the sample operation sequence of shots so as to provide validation. The analysis was run as a series of 19 shots with each shot consisting of an 8 s pulse and a cool down period of varying duration. Typical temperature profiles taken at the end of each type of analysis are shown in Figs. 6(a) and (b). After the pulse, the bulk of the temperature rise occurs in the areas where heat generation as a result of contact resistance is assumed to occur Fig. 6(a). Following the cool down period, however, the warmest parts of the belt bus assembly are the outer flexible straps, the area farthest from the actively cooled

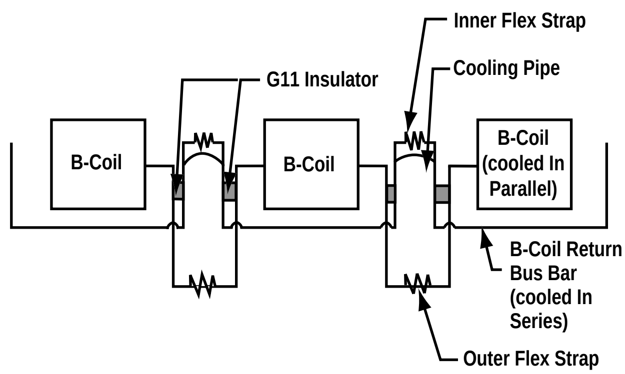

Fig. 5. A simplified schematic of the TF-coils, outer flexible, and inner flexible straps.

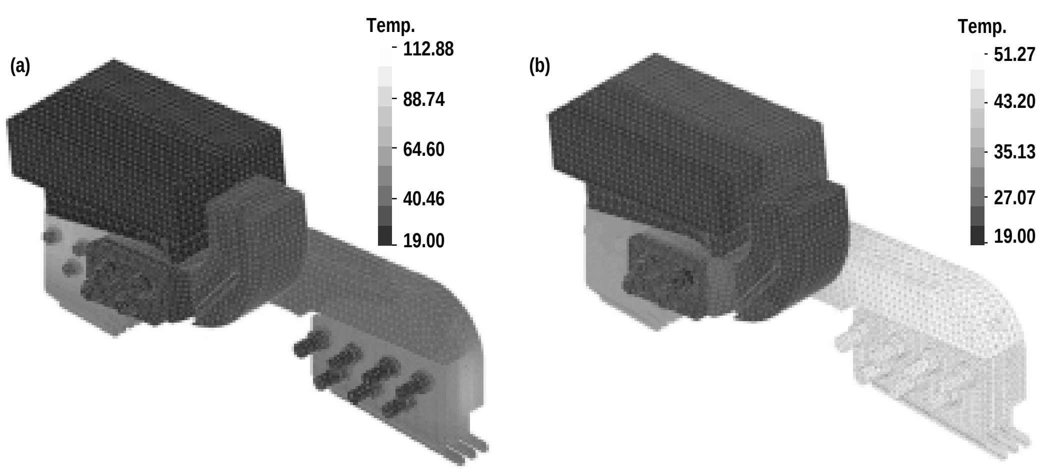

Fig. 6. (a) Typical temperature distribution in the TF-coil belt bus following a pulse and (b) a cool down period. Immediately after the pulse, the heat is concentrated in the areas where there is contact resistance. Following cooldown, the hottest regions are those furthest away from active cooling, the outer flexible straps.

areas Fig. 6(b). For the series of shots, $I_B^2 \cdot t$ values and cooling times were taken from the operations sequence, input into the computer model, and the results plotted in Fig. 2. In this figure the temperature at the top of outer flexible strap as a function of time is plotted along with the observed experimental data (solid curve). The model was first run using an assumption of constant temperature, 20°C, cooling water. As can be seen in the figure, though the trends in the data are generally predicted, there is a gradual divergence between the measured value and the values predicted by the model.

After some investigation, it was determined that the assumed cooling water temperature of a constant 20° was not accurate. Lacking any specific data of cooling water temperatures, a smooth, gradual increase in cooling water temps over the course of the day was assumed. Re-running the analysis with this assumed profile yields the dotted curve in Fig. 2. As shown in the figure, ignoring the fourth shot, the model shows good agreement with the measured data, thus providing validation of the computer model.

Having established reasonable confidence in the accuracy of the model, the analysis was then extrapolated out to simulate a 10 s shot including current rampup and rampdown. A 10 min cool down time was assumed, representing a minimum cool down that would be used during operations. The analysis was run over a series of shots using the same cooling water temperature profile that was used to match the model with experimental results and the results are plotted in Fig. 7(a). In this graph, the maximum temperature of two locations, that of the G11 and of the outer flexible strap, is plotted as a function of time. As can be seen in the figure, the temperature of the G11 material ratchets up and soon approaches the maximum allowable temperature. Also noteworthy is the substantial increase in the temperature of the outer strap just prior to the next shot, rising approximately 90°C over the ten cycles examined.

V. Improvements to the System

As predicted by the analysis, the existing TF-coil belt bus system uncomfortably approaches the maximum G11 allowable temperature during 10 s operation. Furthermore, due to the location of the TF-coil system as well as the subsequent installation of various diagnostic systems in the vicinity of the TF-coil, major modification of the TF-coil system would be difficult, costly, and lengthy. A simple, easily installed, modification is thus desirable. One such modification has been proposed. This modification consists of a water cooled bolt which could be easily installed in the location of pre-existing bolts in a few places on the outer flexible straps. Examining the temperature distribution over the course of the cool down periods, it is evident that the maximum temperature occurs at the location with longest conductive cooling path, the outer flexible straps. This area effectively becomes a heat storage area, contributing to the ratchetting up of the temperature of the system over the course of a series of shots. By installing the water cooled bolts in this location, theoretically, a good portion of the residual heat would be removed.

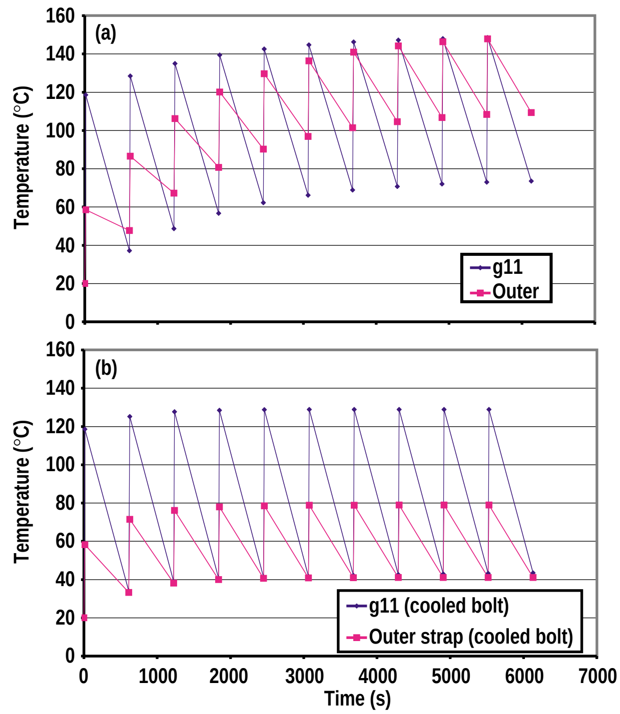

Fig. 7. Predicted response of the TF-coil belt bus system to a series of 10 s pulses with 10 min cool town times. The “as is” system response is shown in (a) which plots the maximum temperature of the G11 and the outer strap. The “modified” system response, assuming two cooled bolts, is shown in (b).

In order to estimate the effect of the addition of two water cooled bolts, the model was modified by adding holes down the center of two bolts on the outer straps. The same convective film coefficients and temperature profiles were added to the surfaces down the bore of the bolts as used elsewhere in the model. The analysis was run using the same parameters as in the 10 s simulations and are plotted in Fig. 7(b) with triangular data points. As shown in the figure the maximum temperature of the G11 is reduced to 135°C, which satisfies the 150°C maximum temperature of G11.

This analysis, however, is based upon a temperature profile which was established in order to match the computer model with one set of experimental data. It does not represent a “worst case” water profile. Futhermore, since the TF-coil return bus bar is plumbed with twelve bus bars in series it may not be representative of the last location in the cooling loop. Referring back to Fig. 5, one can see the temperature of the G11 can be affected by either of the two current loops. Thus, the analysis was re-run using a constant, more conservative, value of 35°C for both the cooling water temperature and initial temperature of the system. The temperature response of the G11 in the nominal system is plotted in Fig. 8(a) as diamond shaped data points. As can be seen in the figure, the temperature of the G11 exceeds the allowable maximum temperature, rising as high as 163°C. Addition of cooling to two of the bolts on the outer flex strap is predicted to reduce the maximum G11 temperature (shown as square data points). An additional case of adding cooling to just one of the bolts

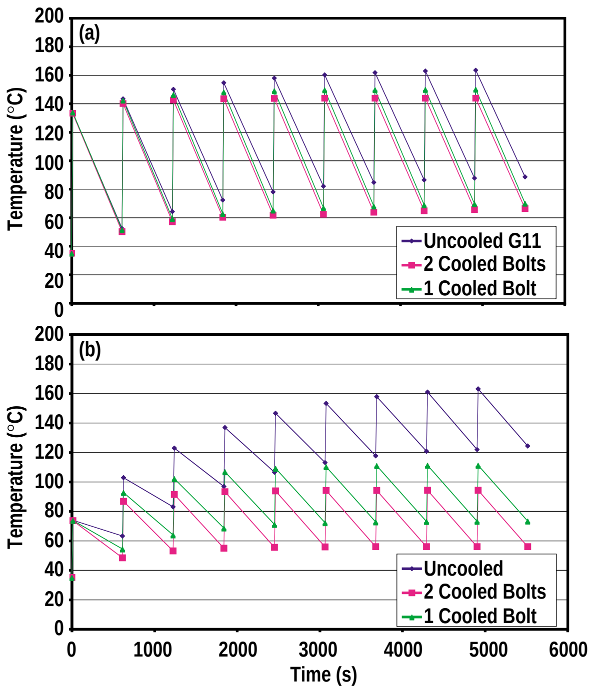

Fig. 8. Predicted response of the TF-coil belt bus system to a series at 10 s pulses with 10 min between pulses and an initial temperature and constant cooling water temperature of 35°C. The system is examined for three cases; "as-is," with two cooled bolts, and with one cooled bolt. The predicted G11 temperature is shown in (a) while the predicted outer strap temperature is shown in (b).

was also examined and is plotted in the figure as triangular data points. The maximum temperature in this case is 150°C. The relative effectiveness of the water cooled bolts is more clearly illustrated in Fig. 8(b) which plots the maximum temperature of the outer flexible strap for the three cases.

VI. CONCLUSIONS

A computer model was constructed in order to extrapolate the thermal behavior of the TF-coil belt bus bar from 5 s of operation to 10 s of operation. After adjusting the cooling water temperature to simulate variations throughout the day, good agreement was achieved between the model and observed experimental results for 5 s pulses. For 10 s operation, the model predicted that the maximum temperature of the G11 material would be exceeded. An easily installed design improvement of water cooled bolts which would be located on the outer straps was simulated and it was predicted that the maximum temperatures would be reduced to acceptable levels.

Experiments are currently being conducted to confirm the effectiveness of the water cooled bolts. Additionally, data will be collected to further characterize the thermal behavior of the system. This will, hopefully, further validate the analysis and suggest other methods of increasing cooling (such as splitting the return bus bar into four loops with six in series).

ACKNOWLEDGMENT

Work supported by U.S. Department of Energy under Contract DE-AC03-99ER54463.

REFERENCES

[1] R.W. Callis, "Status of the DIII–D 110 GHz ECH System," Proc. 12th Top. Mtg. on Technology Fusion Energy, Reno, Nevada, Vol. 30, Part 2A, p. 825.

[2] R. Lee, "TF-coil belt Bus Temperature Summary," Internal memo, 2000.

[3] Solidworks, A 3-D CAD package, Solidworks Corporation, Concord, Massachusetts, USA.

[4] COSMOS, A Finite Element Analysis Code, Structural Research, Santa Monica, California, USA.

[5] C.B. Baxi, "Significant Results of TF-coil Thermo-Mechanical Tests," Internal Memo, 1990.