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Restoration of the DIII–D Solenoid*

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Abstract — The DIII–D tokamak has been operated since June 1995 with constrained ohmic heating capability as imposed by the abandonment of half of it's solenoid system due to a cooling water leak. The solenoid is comprised of "A" and "B" windings with separate multiple power leads to each. The cooling water leak occurred in the lead of the B winding. This leak occurred in a remote area under the DIII–D vessel and is believed to be caused by magnetic forces developing cyclic bending loads on the conductor. Visual inspection of the lead using flexible bore scopes indicated that the structural fiberglass overwrap intended to band the supply and return leads into a primary-force canceling group had failed allowing individual conductors to become inadequately supported against bending loads. The overwrap failed as a result of poor epoxy encapsulation of the lead which was manufactured in 1978. Inspection of the A lead confirmed no overwrap failure and that the vacuum encapsulation of the A lead was proper and to specification.

In order to continue operations, it was decided to abandon the B winding of the solenoid and operate under reduced (5 V-sec) capability.

An *in-situ* repair approach was mandated by the extensive and lengthy effort required to disassemble, repair, and reassemble the tokamak. Access from outside the tokamak was severely limited. A plan to repair the damaged lead was developed and implemented over a 10 month period.

This paper describes the repair of the solenoid lead. A VCR video tape of these remote installation efforts has been assembled and will be shown.

INTRODUCTION

This paper describes the repair implemented for the DIII–D solenoid B winding which developed a water leak in May 1995. This leak was traced to a cracked hollow copper conductor in the lead area which had resulted from excessive deflection due to forces developed by its current flow interacting with the toroidal field of the Tokamak. The solenoid lead is located below the vacuum vessel as shown in Fig. 1. The cooled copper conductors in the coil lead became relatively unrestrained mechanically after the structural failure of the fiberglass overwrap which had functioned to restrain the eight conductors in a rigid group. The overwrap failure is believed to be due to inadequate resin penetration during fabrication which occurred in 1978. The B winding of the solenoid system was disconnected in Summer of 1995 and the A winding has been used for all subsequent operation. In order to assure continued availability of the remaining half solenoid, an interim limit 5 V-sec operation with a peak current of 87.5 KA was imposed. This compares with the normal limit for the total solenoid of 10 V-sec operation with a peak current of 175 KA. Based on visual examination, it is believed that the A solenoid lead was manufactured correctly and does not have the same defect that caused failure in the B solenoid.

Within the overwrap, each of the conductors was overwrapped with ten layers of 5 mil kapton before impregnation. This insulation appears to have remained intact. The failed lead passed normal operational electrical tests after it was dried out. Subsequent tests showed that the multilayer kapton insulation, designed to withstand 30 KVDC in air, also withstood 30 KVDC when water soaked.

The DIII–D solenoid is constructed of a pair of 48 turn coils operated in parallel. Each turn is comprised of four hollow copper conductors about 26 mm square with a 11 mm diameter coolant hole. All power connections are below the vacuum vessel at the end of a horizontal lead. The four parallel conductors route radially inward to the base of the solenoid, form turns 1 through 24 as they wind up the solenoid and turns 25 through 48 as they return down the solenoid before combining into the common lead pack which includes all eight conductors for each half solenoid. Cooling water enters all eight conductors in the lead and flows up the solenoid where it exits above the vessel between turns 24 and 25. Two of the four exit tubes were damaged by sandblasting after the cracked conduction problem occurred. These tubes would require repair in order to restore cooling water to the B windings.

Direct access to areas needing repair was prevented by the existing hardware precluding the use of conventional repair techniques such as replacing fiberglass overwrap. The inspection was done using flexible 8 mm diameter bore scopes. Direct access repair of the lead was not considered reasonable since it requires vessel removal and would shutdown DIII–D for more than a year.

The goal of the solenoid repair program is to restore the solenoid system to 7.5 V-sec operation with a peak current of 140 KA. A plan was developed. The four repair approaches adopted were selected from about 15 ideas that were considered. These four repair tasks are:

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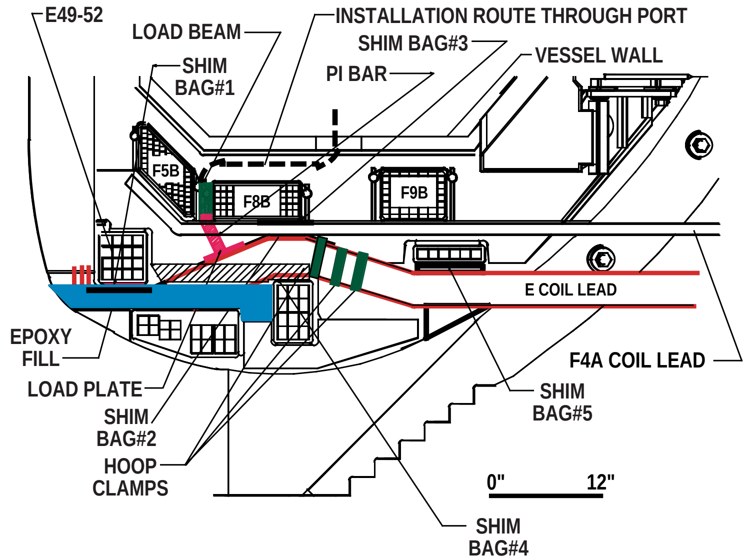

Fig. 1. DIII–D solenoid repair area.

1. Restrain the conductor pack in the lead area using a clamp to produce 23000 Nt (5200 lb) downward preload against the conductors in the lead. This loading will eliminate cyclic deflections in the conductors which would result in continued crack growth. Actively monitor the preload force to assure proper preload condition. Install three band clamps around the lead between the F5B and F8B coils to maintain the conductors in their proper position since the overwrap has failed in the area between the solenoid and the F9B coil.

2. Plug the cracked coolant line in the conductor to prevent further leakage.

3. Repair or plug the two coolant exit tubes at the top of the machine which were damaged during sandblasting to clean the coolant passages. Plugging of these tubes will develop coolant flow paths of twice the standard length with about 80% of the normal coolant velocity.

4. Re-configure the E bus to the original DIII–D configuration and operate the A and B circuits of the solenoid with balanced current as before.

Task 1 was considered to be the most demanding and would be completed successfully before attempting the other tasks. Access through the floor of the vacuum vessel greatly facilitated this task. Fig. 1 shows a vertical cross-section through the lower part of the DIII–D tokamak indicating the solenoid lead, mechanical clamp and bands required for repair.

The basic mechanical clamp (Figs. 1&2) design was developed based on drawing dimensions. The component parts must be remotely positioned either by long handled tools, strings, or by the arm of a technician reaching through the hole in the vessel floor developed by removal of the vertical port. The clamp applies downward force to a load plate which in turn applies pressure to the inclined solenoid lead through shimbag #2. Shimbags are positioned and then pressure filled with epoxy and function to distribute the load evenly to the irregular surface of the lead. The outer end of the shimbag is secured to the solenoid lead with one of three hoop clamps. Placement of the shimbag and clamp installation to constrain the shimbag is done first. Installation of the load plate is then done along a horizontal path parallel to the solenoid lead. A 5 m long concentric tubular handle is used to position the plate past its' final insertion position at which time the plate is rotated 90° about two perpendicular axes and then tilted 25° about the third axis in order to align with the surface of the lead. The load plate is then moved outward on top of shimbag #2. The pi bar (a structural bridge that looks like π) is then brought into position through the vertical port opening, and rotated into place straddling the F4A coil lead and engaging mechanical keys into the load plate to prevent slippage between the pi bar and load plate. The load beam is then brought in through the vertical port with the load arms

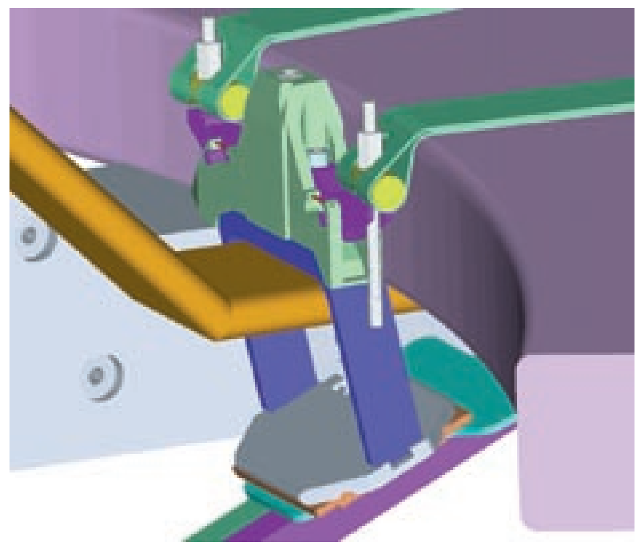

Fig. 2. Solenoid lead clamp system.

retracted to allow the beam to be positioned over the pi bar. Deployment strings and threaded fasteners are used to deploy the arms under the existing coil attachment straps which mount the F8B coil to the structural wagon wheel (radial aligned) beams. Once the arms are tightened into place, the clamp load is applied by rotating the jacking screw located at the top of the load beam. Not shown in the figures are the ratchet wrench and push/pull cable system installed over the jacking screw to allow load additions after the vertical port is reinstalled and the vessel is evacuated.

In August 1996, DIII–D was opened for a planned 5 month period for in-vessel installations. The bottom vertical port at 0° toroidal location was cut off from inside the vessel to provide improved access to the failed area of the lead for measurement of as-built dimensional information. Fig. 3 shows the in-vessel technician with his arm extended through the port hole in the floor of the vessel. Two monitors display views for the in-vessel technician from borescopes operated by a technician outside of the vessel.

CONDITION BEFORE REPAIR

Based on bore scope viewing, the eight conductors were no longer constrained into a group. The leaking kapton wrapped conductor appeared somewhat displaced upward from its' normal condition and was visible through cracks in the overwrap of the lead. The electrical insulation around the conductor pairs appeared undamaged. The structural damage to the overwrap of the lead appeared to be over a length of about 80 cm and existed from the solenoid to below the F9B coil. The lead was reasonably well supported for downward loads but unrestrained against upward loads. Both up and down loading conditions existed for the individual conductors during operation due to reversal of current flow in the lead.

The vertical port was removed which allowed for measurements of the as-built condition of the installation area of the clamp.

The inspection was cumbersome using primarily plastic gages built for specific measurements. This did result in accurate information for most areas of interest. Deviations from drawing dimensions were generally in directions which made the design of the clamp system more challenging. The F4A coil lead was located about 1 cm higher than drawing dimension and the solenoid lead elevation, although not directly measurable due to the presence of the F4A lead, was also about 1 cm higher than drawing dimension. The height of the access path over the F5B coil was near drawing dimension and allowed for a flattened hand to pass between the vessel insulation and the diagnostic coils on top of the F8B coil.

Throughout the course of this inspection and repair activity, technicians developed about a dozen specialized long reach (about 3 m) tools that saw repeated use. There were push tools, hook tools, gripper tools and several prebent, 1.2 cm diameter copper tubes semi-permanently installed for the purpose of forming guide sleeves to rapidly guide the bore scopes to the specific areas of interest.

Fig. 3. Technician operating through port hole in DIII–D.

Initial clamp models were made of wood for ease of fabrication and low electrical risk should they become stuck or trapped in place. Prototypes advanced to plastic (Delrin) with aluminum deployable arms constructed to as-built dimensions. Fig. 4 shows the progression of 4 or 5 generations starting at the top of the figure with wooden models and progressing down to production instrumented components of 7075 aluminum and Inconel 718. Inspection gages are on the left of the photo.

Difficulties occurred in fully deploying the arms on the plastic prototype. The clamp beam was being forced away from the F8B coil due to the equatorial bulge in the overwrap on the coil. This bulge was neither shown on the drawings nor directly measured. The successful trial fit was accomplished by thinning the arms on the prototype. This information was factored into the production design.

The removal of failed shrink tube overwrap from the lead in month four indicated that the tear in the fiberglass structural overwrap extended farther outward than previously known. This extensive failure of the overwrap resulted in the requirement to install three metal strap bands, as shown in Fig. 1, to replace the hoop constraint function of the overwrap. .These stainless band clamps were formed in a C shape with a stud and swing bolt on one end and a slotted captive barrel nut on the other end. Like all hardware installed through the vertical port, it was installed one handed with vision provided by two bore scopes with in-vessel and ex-vessel monitors. Designs were evolved to allow reasonable single handed attachment. These band clamps were tightened to develop 10700 Nt (2400 lbs) of hoop tension in each band.

Remote cleaning of crumbled epoxy debris from the lead area in month four revealed significant radial fractures creating gaps between the eight square conductors as they occur in a single layer under the E49-52 coil near the solenoid. It was determined to stabilize and anchor these by means of epoxy

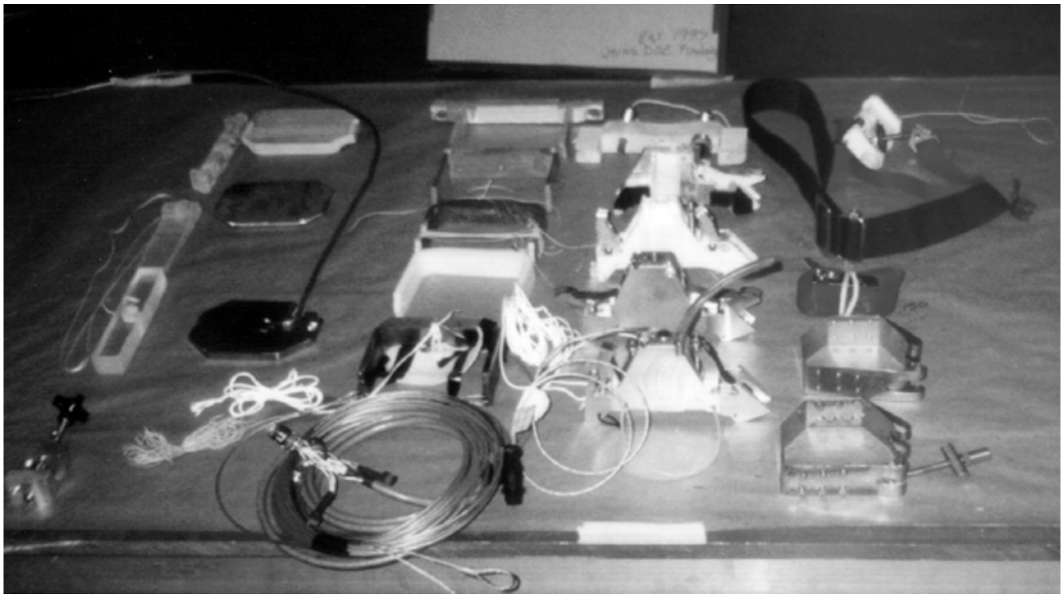

Fig. 4. Progression of mockups to production components.

flooding to the top of the conductors prior to installation of shimbag #1.

An intensive ten week installation period started on January 13, 1997. After vacuum cleaning of the lead area, potential epoxy leak paths were filled remotely with expand-in-place foam. The foam was trimmed as needed and epoxy was filled in 1 cm layers as measured by pre-placed 1 cm cylinders.

Shimbag #1 was delivered through the vertical port, positioned from the port and by use of long handled tools from outside the TF coils, and successfully pressure filled with epoxy.

By mid February all production hardware had been received and was fully instrumented and calibrated to 116% of the 23000 Nt design load.

Installation of the clamp components produced many challenges. These included tangled positioning and retrieval strings, tangles with existing I&C wiring, broken retrieval strings, special tools, etc.

Unknown at the time, February 20 was the start of a 20 day installation period that would require daily in-vessel technician and ex-vessel video operator activities for each of the 20 days. The clamp was installed and fully loaded by day 15 of this period. Although fully loaded, the pi bar had contacted and depressed the horizontal portion of the F4A lead about 1 mm. Analysis indicated that a F4A lead deflection of 2.5 mm would develop unacceptable stresses in the F4A lead. Concern with these stresses and the unknown added travel which may be necessary to maintain the preload led to the decision to replace the pi bar with the newer design which provided for an additional 2.5 mm of travel. The pi bar was removed, replaced and fully loaded in five days including the installation of the remote tightening system.

The final installation resulted in approximately 1.5 mm clearance between the pi bar and the F4A coil lead. This indicates room for additional remote loading which may be necessary due to settlement. The 1.5 mm clearance should increase during operation due to temperature increase in the F4A coil lead.

The clamp system has performed as intended. The initial 1.2 mm of clamp travel loaded against a soft coil lead (probably deformed upper conductors and soft shimbag material) but then the spring rate increased a factor of 5 and became linear for the majority of the loading process. During the first 2 days after initial loading the load dropped off less than 2% due to settlement of less than 0.12 mm. The desired load was restored remotely from outside the vessel. Over the next 5 months the load relaxed an additional 8%. A reduction of 20% is acceptable and maintains adequate load for operation.

Electrical testing showed that the lead was electrically acceptable for routine use. The 0° V-1 port was installed, welded and leak checked on March 21, 1997.

Restoration of the leaking water cooling circuits was mostly accomplished in the Summer of 1997 with completion expected by October 1997. This effort included remote cutting and remote soldering of 12 mm o.d. copper tube at the top of the machine and remote installation of expandable elastomer plugs in the leads at the bottom of the machine. Electrical bus modifications and other changes are scheduled for November 1997 to restore the solenoid to 7.5 V-sec operation starting in 1998.

REFERENCES

[1] E.E. Reis, *et al.*, “Analysis and testing of the DIII–D ohmic heating coil lead repair clamp,” this conference.
[2] C.B. Baxi, *et al.*, “Thermal analysis and testing for DIII–D ohmic heating coil repair,” this conference.