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*Lawrence Livermore National Laboratory

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Performance and Development of the DIII–D Tokamak Core

P.M. Anderson, W.R. Johnson, J.L. Busath, and S.L. Allen[1]

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

ABSTRACT

The DIII--D tokamak is an upgrade of the Doublet III configuration which has operated since early 1986. This paper presents recent advances in performance using the upper divertor, fabrication development for vanadium components, operation of the helium leak checking in a high deuterium background, and restoration of the damaged Ohmic heating solenoid.

1. DIII–D UPPER DIVERTOR BAFFLE AND PUMP

Density control is important in DIII–D experiments because the efficiency of the radio frequency sources used to drive non-inductive currents decreases with density. We have installed and operated a new upper divertor baffle and cryopump (deuterium pumping speed ~40 k ls^{-1}), to control the core electron density in high-triangularity discharges as shown in Fig. 1. Electromagnetic forces from ‘‘halo currents’’ induced by disruptions were an integral part of the design. In ELMing H–mode plasmas, we have reduced the ‘‘natural’’ (no gas puffing) core density from $n_e / n_{GW} \sim 0.5–0.6$ to 0.3 with cryopumping, where n_{GW} is the Greenwald density. In single null divertor discharges, with plasma current $I_p = 1.6$ MA, the core plasma is ‘‘clean,’’ with $Z_{eff} \sim 2.0$ and $\tau_E / \tau_{E\ ITER\text{-}89P}$ (the ratio of the energy confinement time to ITER89-P scaling) ~ 1.8, *i.e.*, good H–mode confinement. Preliminary high-triangularity double null operation has shown that the measured exhaust in double null (with the plasma only coupled to the single upper pump) is about half (10 T ls^{-1}) of the upper single-null rate (~17–20 T ls^{-1}). We have been able to vary the exhaust of the upper pump by varying the up/down magnetic balance of the plasma. We have two more planned divertor modifications: first, in 1999, an installation of an upper-inner pump, followed by a double null installation with four cryopumps in 2001 [1].

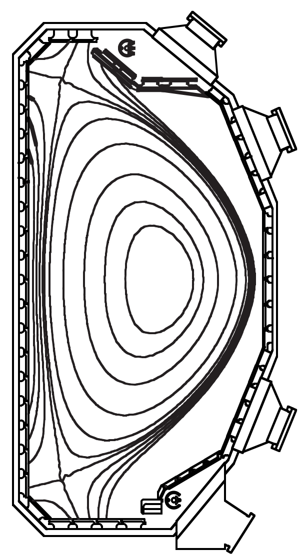

Fig. 1. DIII–D with lower cryopump for open lower divertor and upper cryopump for shaped upper divertor.

2. DIII–D VANADIUM FABRICATION DEVELOPMENT

General Atomics, in conjunction with the Department of Energy's DIII–D Program, has carried out a vanadium manufacturing development plan as part of the DIII–D

[1]Lawrence Livermore National Laboratory, Livermore, California.

Radiative Divertor upgrade. The V-4Cr-4Ti alloy has been selected in the U.S. as the leading candidate vanadium alloy for fusion applications. This alloy may be used for the divertor fabrication.

Several product forms and types of metal/metal bonded joints have been developed. Several solid state (non-fusion welded) and fusion welded joining methods have been investigated. General Atomics was successful in producing ductile, high-strength, vacuum leak-tight joints by all of the methods investigated. The solid-state joining was done in air without the need for a vacuum or inert gas environment to prevent interstitial impurity contamination of the V-4Cr-4Ti alloy [2].

3. DIII–D LEAK CHECK SYSTEM UPGRADE

Maintaining vacuum in the 10^{-8} Torr range is crucial for producing high performance plasma discharges. He leak detection at DIII-D has historically been challenging. The difficulty lies in the substantial inventory of D_2 from discharge fueling and He from glow discharge cleaning that saturates the graphite armor tiles that protect the interior walls of the tokamak from the plasma discharges. The mass of the D2 molecule (4.028 amu) is indistinguishable from that of He atoms (4.003 amu) to a standard mass spectrometer leak detector. High partial pressures of D_2, outgassing from the system components, reduce leak detector sensitivity and effectively mask the He trace gas signal, rendering normal leak checking techniques ineffective for small leaks.

Previous methods for dealing with high D_2 backgrounds have used cryo-pumping, titanium gettering and ZrAl gettering. These methods required permanently installed complex systems, were short lived, or required high vacuum for operation and/or extremely high temperatures for activation. The ZrAl getter has been shown to achieve a best case reduction of D_2 levels by a factor of 250 [3].

A different approach is employed at DIII–D. Instead of differentially pumping D_2 from the sample stream to the leak detector, the sample stream is passed through a portable catalyst filled reaction chamber that facilitates the formation of D_2O and DHO. The oxygen and hydrogen in the gas mix necessary for these reactions comes from small air leaks and the cracking of water vapor present in the leaks. The resultant heavy water compounds are easily distinguished from helium by the mass spectrometer.

The effectiveness of catalytic D_2 removal was shown during a bench top comparison of RGA and leak detector readings with and without benefit of a catalyst cell. The observed $>10^4$ reduction in D2 levels restores sufficient leak detector He sensitivity for effective leak checking of DIII–D. Ultimate leak detector sensitivity is dependent on the background levels of residual He present. For long term use or between leak checks, the bulk catalyst temperature must be raised above 60˘ C to ensure complete catalysis and outgassing of heavy water byproducts [4].

4. DIII–D SOLENOID REPAIR

One of two parallel DIII–D Ohmic heating solenoids developed a water leak in May 1995. This leak was traced to a cracked hollow copper conductor in the solenoid lead which had resulted from excessive deflection due to forces developed by its current flow interacting with the B field of the tokamak. The cooled copper conductors in the coil lead became unconstrained after failure of the fiberglass overwrap which had maintained 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 solenoid was disconnected in summer of 1995 and the other was used while repairs were underway. Because of current limits on the remaining solenoid, an interim limit 5 Vs operation with a peak current of 70 kA was imposed. This compares with the normal limit for the total solenoid of 10 Vs operation with a peak current of 175 kA. It is believed that the remaining solenoid lead was manufactured correctly.

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 and water connections are below the vacuum vessel at the end of a horizontal lead.

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 with built in lights. The goal of the solenoid repair program was to restore the solenoid system to 7.5 Vs operation with a peak current of 140 kA. The four main repair tasks were:

1. Restrain the conductor pack in the lead area using a clamp to produce 23000 Nt (5200 pound) downward preload of conductors in the lead against a solid surface. This loading will eliminate cyclic deflections in the conductors which should stop crack growth. Actively monitor the preload force to assure proper preload condition. Install three band clamps around the lead outboard of the clamp to maintain the conductors in their proper position.
2. Seal the crack in the conductor to prevent further leakage.
3. Seal leaks in the two coolant exit tubes at the top of the machine. These thin wall copper tubes were damaged during sandblasting to clean the coolant passages.
4. Re configure the bus to the original DIII–D configuration and operate the solenoid in parallel.

Of the four tasks above, only Task 1 required access from inside the vacuum vessel. This task was considered to be the most demanding and was completed successfully before attempting the other tasks. Figure 2 shows a vertical cross-section through the lower part of the DIII–D tokamak indicating the solenoid lead, mechanical clamp and bands.

The basic mechanical clamp design was developed based on drawing dimensions for the surrounding components and updated based on as-built measurements. The clamp applies downward force to a load plate which in turn applies pressure to the inclined solenoid lead. 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 was reinstalled. All production hardware was fully instrumented and calibrated to 116% of the 23000 Nt design load.

Failure of the lead overwrap resulted in the requirement to install three metal strap bands, as shown in Fig. 2, to replace the hoop constraint function of the failed overwrap. Designs were evolved to allow reasonable remote attachment. These band clamps were tightened to develop 10700 Nt of hoop tension in each band.

The clamp system has performed as intended. After the initial 1.2 mm of clamp travel loaded against the coil lead the stiffness increased and became linear for the majority of the loading process. Acceptable load has been maintained over a one year period by remotely tightening the load screw. There has been 1.2 mm of creep in the system which has now stabilized.

Restoration of the leaking water cooling circuits was completed in January 1998. This effort included remote cutting and remote soldering of 12.7 mm o.d. copper tubes at the top of the machine and remote installation of a dual expandable elastomer plug straddling the crack in the conductor at the bottom of the machine. This plug allows restricted cooling water flow and

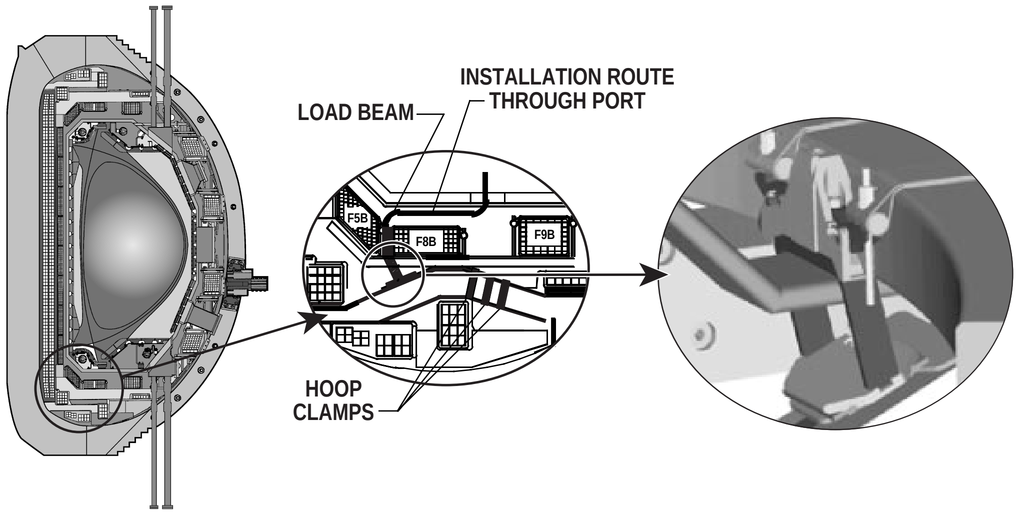

Fig. 2. Vertical cross-ection of the DIII–D showing location of solenoid failure and repair using lead clamp and hoop clamps to stabilize lead conductors.

incorporates a high pressure nitrogen gas buffer between the elastomers which then flows out through the crack. The nitrogen gas flow rate has diminished over time to about 10% of its initial flow rate indicating that the crack growth has stopped and that the clamp load is producing a pinching effect on the crack. The full solenoid had been operated to 7.5 V-s operation since February 1998. Refer to [5] for mechanical details and [6] for cooling system analysis and testing.

ACKNOWLEDGMENT

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