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OPERATION OF DIII-D WITH ALL-GRAPHITE WALLS

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ABSTRACT

Recently, additional graphite coverage has been installed in the DIII-D tokamak, increasing the graphite tile coverage from 45% to ~90% (limited only by openings for ports). Due to a problem with copper impurity bursts during tokamak discharges, copper foam sheets between the graphite tiles and the Inconel wall have been replaced with GRAFOIL gaskets (a compressible graphite material), which further increases the surface area of the graphite inside the DIII-D torus. Although additional graphite has the potential for improving DIII-D performance, if not properly conditioned it can also degrade tokamak discharges by contributing to increased low Z impurity influx (C and O) and higher particle fueling (D). To address these concerns, improvements were implemented both in tile preparation and wall conditioning techniques. All previously installed tiles were grit-blasted with boron-carbide grit to remove co-deposited metal impurities and all tiles were outgassed to 1000°C prior to installation. The glow discharge system used for wall conditioning was modified to include a large area electrode (0.32 m²). The only conditioning techniques used were baking and helium conditioning (glow and Taylor discharge cleaning) to avoid producing loosely bound carbon. Previously, H₂ or D₂ Taylor discharge cleaning was used extensively during the vent recovery phase. Recovery from the recent 7-month machine opening was extremely rapid with improved modes of energy confinement (H-mode) transitions observed on the 14th plasma discharge. In addition, very high confinement (VH-mode) discharges were obtained without boronization, which is further indication of the rapid vent recovery. Lower recycling/lower fueling efficiency was also observed during operation with all-graphite walls. We will also discuss the use of Ne and Ar glow, and qualification of the new graphite including outgassing tests of the GRAFOIL material.

I. INTRODUCTION

The DIII-D tokamak is a device used for magnetic fusion research. It has an Inconel vacuum vessel and is designed for ultra-high vacuum, $P > 2.0 \times 10^{-8}$ Torr. In operation since 1986 at General Atomics, it includes magnetic coils for plasma heating and shaping, and auxiliary plasma heating systems and diagnostic systems. The vessel itself is a toroidal shell with a D-shaped cross section. It has a volume of 35 m^3 , a major radius of 1.67 meters and a minor radius of 0.67 meters. During the shutdown from June 1992 to January 1993 graphite coverage of plasma facing surfaces was increased from 45% to 90%. Since nearly all of the remaining uncovered surfaces are port openings, we refer to this increased coverage as an all-graphite wall. The purpose of installing the all-graphite wall in DIII-D was to reduce metallic impurity influx into plasma discharges. In previous campaigns metal impurities were observed spectroscopically, particularly in high performance ELM-free discharges. The dominant metal impurity was nickel, which was the main component of the exposed Inconel outer wall of DIII-D.¹ To reduce this source of metal impurity contamination, the outside wall was armored with graphite tiles. In parallel with this modification, additional work was done to reduce other sources of impurity contamination. First, all tiles which had been previously installed were grit blasted with a boron carbide grit to remove impurities. Secondly, copper foam sheets were replaced with GRAFOIL, a porous and compressible form of graphite. The copper foam had been previously installed between graphite tiles and the Inconel wall to increase thermal conductivity, while decreasing stress concentrations. However, small flakes of copper fell into plasma discharges producing bursts which were sometimes severe enough to disrupt the discharge. It was found that the GRAFOIL could serve the function adequately. In the 1993 results to date, the copper bursts have been eliminated and the nickel has been reduced to a very low level and is no longer a problem.

Operations with the all-graphite wall have been very successful (Section 2). In addition, to the reduction of impurities, H-mode discharges (indicating clean wall conditions) were rapidly reestablished. The operating regime of DIII-D was expanded with the first observations of VH-mode without boronization and full field (2.1 T) ohmic H-modes.

The previous major addition of graphite tile coverage (1987/1988) required a long period of conditioning before H-mode was achieved. In contrast, vent recovery from the all-graphite wall coverage has been very rapid. Two important factors contributed to the successful vent recovery with the all graphite wall and the drastic decrease in the amount of conditioning required before H-mode was achieved. First, all tiles were carefully preconditioned before installation. Second, no hydrogen or deuterium was used during post-vent conditioning; the only use of deuterium was to fuel the tokamak discharges (Section 3).

The increased graphite coverage raised concerns over whether our current standard DIII-D vessel conditioning methods would be adequate to achieve the low recycling needed for good plasma discharges. Several improvements were evaluated and these are discussed in Section 4. These improvements include the use of Ar and Ne as compared to He as the fueling gas for glow discharge conditioning and the effects of a larger surface glow electrode.

Finally, conclusions and results will be discussed in Section 5.

2. INITIAL RESULTS WITH THE ALL-GRAPHITE WALL

After the 6-month machine opening to install additional graphite tiles, the vessel recovered very rapidly. On the 14th plasma attempt, which was the 5th discharge with neutral beam heating, H-mode transitions were observed. H-mode is a regime of high particle and energy confinement time requiring low particle recycling and low impurity levels.² This recovery is much quicker than during the last large increase in graphite coverage which occurred in 1987 when the plasma surface area of graphite was increased from 9% (1985–1987) to 40% (1988–1991). After this upgrade H-mode discharges could not be reestablished. Even after extensive cleaning (high temperature baking and full power tokamak discharges) it was not until the development of He glow wall conditioning that H-mode discharges were again achieved.³ As can be seen in Table 1, the number of discharges required has been decreased from 380 to 14 and the total conditioning time has been reduced by a factor of 4 from approximately 200 h down to 50 h.

TABLE 1

	1987 Vent (9% to 40% Recovery After Graphite Coverage)	1992 Vent (45% to ~100% Recovery After Graphite Coverage)
Baking	130 h	47 h
Baking and Taylor discharge cleaning	>70 h (D ₂)	3.5 h (He)
He glow and baking	—	3 h
No of tokamak discharges before first H-mode	380	14
HeGWC (helium glow wall conditioning before every discharge)	Developed during vent recovery period	Yes

The first observation of full toroidal field ohmic H-mode transitions were observed. Ohmic H-mode discharges require a well conditioned machine with low density, low recycling, low radiated power and a low impurity level. Until the installation of the all-graphite wall full field ohmic H-mode discharges had not been observed in DIII-D.

VH-mode (a very high confinement-mode which is sensitive to machine conditions requiring low Z_{eff} , low target density and low recycling⁴) was obtained without boronization. This operational mode had only occurred previously in the vessel after boronization was implemented. Boronization is a process where a thin film of boron (80–100 nm) is laid down over the surface of the vessel. It lowers recycling and decreases impurity levels especially oxygen. Figure 1 shows the characteristic of two similar VH-modes, one from before the vent with boronized graphite and Inconel walls, and one after the vent with the all-graphite unboronized wall. The power that is radiated away due to impurities, P_{rad} , is significantly lower in the unboronized all-graphite wall.

As discussed in Section 1, the main purpose of the all-graphite wall was to reduce impurity influx during tokamak discharges. Observation of UV spectroscopic impurity line radiation, shown in Fig. 2, demonstrates that metallic impurities have been reduced. For the 1993 VH-mode discharge, with the all-graphite wall, nickel (Ni XXVI) shows very little increase in intensity during the VH-mode phase and the transition back to ELMing H-mode. In contrast, the Ni XXVI line for a similar 1992 discharge show a gradual increase implying an influx of metals into the discharge. An example of copper bursts (Cu XIX) which occurred during 1992 discharges is also shown in Fig. 2. The elimination of copper gaskets and their replacement with GRAFOIL has led to the elimination of copper bursts during discharges for the 1993 campaign.

There was concern before plasma operations began that the increased graphite coverage would cause a high influx of carbon atoms, but this is not the case. The carbon levels have not increased significantly.

Fig. 1. For similar discharges radiated power is significantly reduced with the unboronized all-graphite wall as compared to the boronized wall before the all-graphite installation ($I_p = 1.6$ MA, $B_t = 2.1$ T).

Fig. 2. UV impurity line radiation is generally reduced from before (dashed line) to after (solid line) the installation of the all-graphite wall. Nickel (Ni XXVI) does not increase during the discharge, and copper bursts (CU XIX) have been eliminated.

3. VESSEL CONDITIONING WITH THE ALL-GRAPHITE WALL

As discussed in Section 1, vent recovery was quite rapid and proceeded more quickly than anticipated. Two factors which may have contributed to this were careful preconditioning of vessel tiles and improved vessel conditioning techniques after pumpdown.

During machine opening, all of the graphite tiles were removed from DIII-D. These tiles were grit-blasted using boron carbide to remove impurities from their surfaces. Analysis of a few graphite tiles previously removed during previous vents had shown a steady increase in metal impurity contamination in the tile surfaces with exposure time, which is correlated with the number of discharges.⁵ These tiles were grit blasted using 37 micron diameter B₄C pellets.⁶ An estimated 20 to 40 microns of material was removed from the graphite surfaces. Figure 3 is a micrograph of the surface of a graphite tile (a) before and (b) after grit blasting. The bright areas are regions of metal deposition. The remaining bright spots in Fig. 3(b) are evident on all graphite surfaces, not just plasma facing surfaces and have been observed in virgin graphite.^{5,7} These microscopic impurities are predominantly iron and are probably introduced during the manufacturing process. It should be noted that iron contamination of DIII-D has not been a problem. Both these micrographs and Auger analysis of the surface indicate that after grit-blasting, metal impurities in the surface and near surfaces are dramatically reduced.

After grit blasting, the tiles removed from DIII-D were alcohol cleaned in an ultrasonic cleaner, dried, cleaned with a cotton cloth and then vacuum baked to 1000°C for 4 h. The new graphite tiles to armor the outside wall were also vacuum baked. Although similar baking had been done in the past, some modifications to the procedures were made and careful process control was implemented during this vent in order to both improve the quality of the outgassing and to

(a)

(b)

Fig. 3. Photograph of a portion of a tile surface (a) removed from DIII-D and (b) a similar tile after grit blasting to remove impurities. Metal impurities are visible in (a) as bright areas, but are greatly reduced after grit blasting.

verify that the process was successfully performed on all tiles. This process included the leak checking of all ovens, specification of the maximum allowable leak rate, the use of a graphite or molybdenum oven liner to reduce impurity contamination, requirements for permanent records of temperature and pressure for each baking cycle, and the insertion of test samples with the graphite tiles for each baking cycle. The test samples were checked for surface contamination levels using Auger analysis at the end of the baking process. Prior to the baking of any graphite, a certifying bake run to 1050°C with samples was performed to determine whether the oven had contaminants which could become liberated at high temperatures. If the ovens were used for any process other than the outgassing of graphite then the certifying bake cycle was repeated. Following the bake, the tiles were cooled down in vacuum to below 300°C, vented in an inert gas (Ar) during the cooldown from 300°C to 80°C, and only exposed to air at temperatures below 80°C. The inert gas is introduced at 300°C, which is 50°C less than the bakeout temperature (350°C) of the DIII-D vessel. Any Ar introduced into the tiles at 300°C should outgas during the 350°C bakeout of the vessel. Although this cooldown procedure was slower than used in the past, it guaranteed that the benefits of the high temperature bake was maintained. The GRAFOIL gasket material, which is placed between the graphite tiles and the Inconel wall was also pre-conditioned following the same procedures. GRAFOIL is a porous and compressible graphite and replaced the copper foam material which had been previously installed. Due to its porosity there was concern that it might be very difficult to outgas. A vacuum test stand was set up to determine the outgassing characteristics of the GRAFOIL. After outgassing as described above groups of approximately 100 GRAFOIL gaskets were subjected to the cleaning cycle they would encounter in the vessel. The gaskets were baked to 350°C for approximately 40 h. They were cooled in vacuum down to room temperature and then the outgassing rate was determined by shutting off the pumping to the system and measuring the pressure rise. The pressure rise of the GRAFOIL after a baking run was compared to the pressure rise in an empty oven after a baking run. This test was repeated multiple times to insure reproducibility. The outgassing rate of a group of approximately 100

GRAFOIL gaskets was measured to be 4×10^{-9} Torr-ℓ/s which corresponds to an outgassing rate per unit area of 2.6×10^{-13} Torr-ℓ/s-cm². Extrapolating the results to the approximately 13,000 20 mil thick and 3000 80 mil thick gaskets installed, the outgassing rate of the DIII-D vessel would be increased by 5.5×10^{-7} Torr-ℓ/s. In comparison, the typical outgassing/leak rate for the vessel prior to the all-graphite wall was $2.0\text{--}5.0 \times 10^{-5}$ Torr-ℓ/s.

After installation, the inside graphite surfaces were wiped with alcohol to remove loose carbon dust and the machine was pumped down and leak checked. Before plasma operations were initiated, 47 h of baking to 350°C, 3.5 h of baking and helium Taylor discharge cleaning (TDC), and 3 h of helium glow with the vessel at 350°C were done (Table 1).

The exclusive use of helium glow for conditioning during vent recovery is a significant departure from previous campaigns. In the past, both hydrogen and deuterium were extensively used during the vent recovery phase. With the all-graphite wall, only helium glow discharge conditioning was used because of the concern that H₂ or D₂ conditioning can create excessive hydrocarbon impurity gases. This problem is exacerbated with the increased graphite coverage. Only a small fraction of these gases are actually removed; the rest are redeposited on the walls. The impact energy of these hydrocarbons is generally low, so they create a loosely bound carbon layer, i.e. soot, when they strike the wall. This sooty layer has a large surface area, and both the adsorbed hydrogen/deuterium and the carbon are easily desorbed, contributing to a high particle fueling rate and high carbon influx during tokamak discharges.^{8,9} The purpose of the helium glow is to minimize this interaction. Helium glow is effective in desorbing oxygen in the form of CO, so no additional conditioning is needed.

4. GLOW DISCHARGE CONDITIONING EXPERIMENTS

The problems with vessel recovery in the 1987 vent when the graphite coverage was increased from 9% to 40% raised concerns over the ability to condition the newly installed all-graphite wall. Since glow discharge cleaning is the primary wall conditioning technique on DIII-D, techniques to improve the efficiency of the glow system were implemented. These include the use of Ar and Ne discharges and the use of as larger electrode both of which are discussed below. In addition, possible differences in the glow current density to the Inconel wall and graphite tiles was investigated.

Before the vent the glow discharge system in DIII-D consisted of two graphite (0.025 m^2) electrodes recessed in ports each connected through variable resistors ($150\text{--}2500 \Omega$) to a separate 900 V /4.5 A power supply. The normal glow parameters were $P_{\text{abs}} = 2\text{--}5 \text{ mTorr}$, $V_{\text{anode}} = 300 \text{ V}$ and $I_{\text{total}} = 6 \text{ A}$.

Previous experiments had indicated that a large area electrode was more effective than a small area electrode in conditioning the vessel walls.³ To further investigate this, a large area (0.32 m^2) graphite electrode was compared with the two smaller area electrodes (0.025 m^2 each) normally used for glow discharge conditioning. As shown in Fig. 4 the current from the smaller area electrodes declines much more rapidly than for the larger electrode as the pressure decreases. In addition, the glow with the large area electrode is much more stable and can be sustained in a lower pressure range (0.5 mTorr as compared to 2.0 mTorr for the smaller area electrode). At the lower pressure, glow voltages of $325\text{--}450 \text{ V}$ can be obtained as compared to voltages of $200\text{--}250 \text{ V}$ at the higher pressures. Since impurity removal rates increase with higher voltage levels for constant

Fig. 4. The current in the glow using a large area electrode compared to the two small area electrodes as a function of pressure.

current conditions the larger area electrode provides a glow that is more effective in removing impurities than the smaller electrodes. Based on this the glow discharge system now uses the larger area electrode.

The effectiveness of a glow discharge is determined by tracking the removal rates of mass 28 on a residual gas analyzer (RGA). Mass 28 is associated with CO, C₂H₄, C₂D₂, and N₂.

However, from observation of the cracking fraction increased mass 28 levels are likely due to the formation of CO, and thus indicate the effectiveness of the glow discharge in removing oxygen. The mass 28 level was obtained for a glow discharge in which the glow gas alternated between Ar and He and then Ne and He (Fig. 5). Although the RGA system is only approximately calibrated, the CO partial pressure for both Ar and Ne glow discharge is considerably higher than for the following He glow discharge. The decline in CO from the second to the third He glow session is due to a reduction in the glow pressure. The gradual decrease in the CO partial pressure in the glow sessions indicates a cleanup of the vessel. The increase in the CO partial pressure may be due to the much higher voltage and hence deeper penetration that can be sustained with Ar (470 V) and Ne (360 V) as opposed to He (230 V).

Due to concerns over the retention of Ne or Ar in the graphite tiles, Ne or Ar glow discharge conditioning was to be used only in case of difficulties in vessel recovery. Even small amounts of these higher Z gases could degrade tokamak performance. The techniques were not extensively used due to the rapidity of the vent recovery using standard vessel conditioning techniques.

There was a concern that the current in the glow discharge might preferentially flow to the exposed Inconel wall as opposed to the graphite wall due to differences in secondary electron emission between the two materials. Increasing the graphite coverage could reduce the current and thus hinder the glow discharge. However, the current to various graphite electrodes in the vessel was measured and found to be in the proper distribution for an uniform current distribution to both graphite tiles and to the Inconel wall.

Fig. 5 The CO value in arbitrary units showing the difference in desorption for Ar glow, Ne glow and He glow

5. DISCUSSION AND CONCLUSIONS

Preliminary results from experiments with increased graphite coverage have been very successful.

Once hardware checkout and vacuum leak repair had been accomplished, vent recovery proceeded much more rapidly than has been observed in the past, particularly when compared to the last major addition of graphite tiles in 1987–1988. Although difficult to substantiate, we feel that two factors contributed most to the rapid recovery and subsequent enhanced operation, namely, careful preconditioning of the vessel tiles and the absence of hydrogen/deuterium during vessel conditioning. Both of these factors were discussed at length in Section 3.

Metal impurities have been reduced and with the addition of the GRAFOIL gaskets copper bursts are no longer a problem. No significant increase in the carbon level has been observed. The increased graphite coverage has not led to any problems in recycling. Recycling with the all-graphite wall is lower than before the increased graphite coverage. These conditions have extended the operational space for DIII-D with the achievement of VH-mode without boronization and the observation of ohmic H-mode at full toroidal field.

With the addition of the all-graphite wall, DIII-D will be in a strong position to carry out the upcoming physics experiments, particularly in the areas of VH-mode confinement physics and stability, radiative divertors, and rf current drive.

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