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INSTALLATION, FEATURES, AND CAPABILITIES OF THE DIII–D ADVANCED TOKAMAK RADIATIVE DIVERTORS

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ABSTRACT

The DIII–D program has completed a series of density control and plasma core confinement experiments this past year. These experiments were designed to investigate the performance of baffled and open divertors with single-null plasmas and particle control in double-null plasmas. The experiments utilized all three of the DIII–D divertor assemblies located in the lower outer corner, the upper outer corner, and the upper inner corner of the vessel, which was installed last year.

Each divertor consists of a liquid helium cryopump, a shielded protective ring, and a gas puff system. The divertors were designed to optimize pumping performance and to withstand the electromagnetic loads from both halo and toroidal, induced currents. With theoretical pumping speeds varying from 15,000 to 32,000 l/s, the cryopumps, combined with the baffle structures, collect particles and prevent them from recirculating back into the plasma core. The intent of the gas puff systems is to inject neutral gases in and around the divertors to minimize the heat flux on the divertors, minimizing the impurities generated by the excessive heating of the divertor graphite tiles. This hardware permits either single- or double-null plasma experiments and enables continued research of well confined high beta divertor plasmas with noninductive current drive, which is one of the primary research goals of DIII–D.

1. INTRODUCTION

Installation was completed in the fall of 1999 of the upper inner divertor (phase 1B) of the Radiative Divertor Program (RDP). In conjunction with the two earlier phases of the RDP, the upper outer divertor (Phase 1A) and the advanced divertor [1] (located in the lower outer quadrant of the vessel), this divertor (see Fig. 1) allows for the study of heat flux reduction in the divertor as well as particle and impurity control for high triangularity plasma discharges.

All three of the divertors have in common a baffle structure that permits the plasma heat flux to be distributed via radiation. This has the effect of reducing the energetic particle impingement onto the divertor structures, specifically the strikepoints. The baffle structures accomplish this by neutral gases that are puffed into the region and allow for

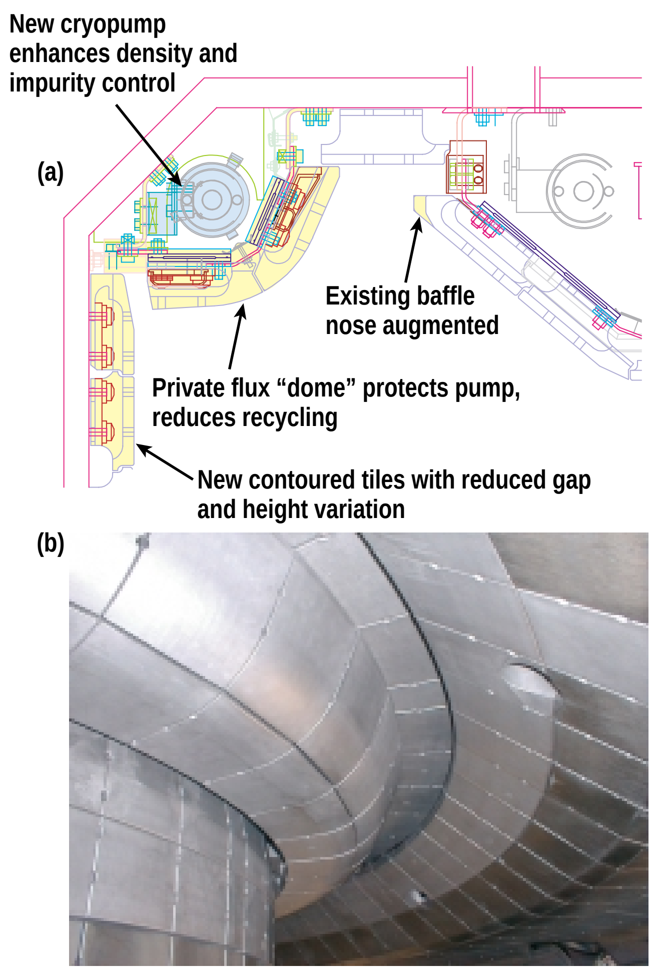

Fig. 1. (a) A cross section view of the AT divertor. (b) A view of the upper divertor after the recent modification.

the radiation/redistribution of the plasma heat flux. Due to the geometry of the baffle structures relative to the plasma, the transport of the neutral gases and impurities into the core of the plasma is limited. Either single- or double-null plasma configurations can be run with this divertor hardware. The design enables continued research of well-confined high beta divertor plasmas with noninductive current drive.

Each divertor structure has a cryopump, that in conjunction with the baffles, collects particles thus preventing them from re-circulating back into the plasma core. Between plasma shots the pump is warmed up and the particles are exhausted from the cryopump surface. Pumping directly above and outboard of the private flux region is possible by the location of two cryopumps on the top of vessel. A variety of diagnostics such as Langmuir probes, bolometers, ASDEX pressure gauges, various spectroscopic equipment and current monitors [2], positioned around the divertors are used to monitor the scrape-off layer, plasma and separatrix in order to analyze impurity transport and plasma flows.

2. CRYOCONDENSATION PUMP

The cryopump in all three divertor systems is a toroidally continuous, space-saving coaxial tube. The continuous tubes minimize the potential of electrical breakdown between the cryopumps and the vessel wall. The inner 2.5 cm diameter Inconel tube of the coaxial arrangement is cooled with liquid helium to 4.3 K. This inner tube is electrically insulated from the surrounding 8 cm diameter liquid nitrogen shield. The liquid-cooled nitrogen shield serves as the primary structural support of the cryopump and limits the heat flux onto the helium-cooled tube. The nitrogen shield is, in turn, surrounded by a 9.5 cm diameter particle shield, which limits the impact of particles onto the nitrogen shield and prevents vapors from desorption. The cryopump is attached to the vessel with a series of brackets that are stiff vertically yet flexible radially for thermal expansion and contraction. Thermal analyses and tests of cryopump design have shown that the helium tube can absorb a transient heat load up to 100 W for 10 s and still pump deuterium at 6.3 K, even though the particle load is less than 12 W during plasma operation [3].

3. DIAGNOSTICS

The performance of the plasma is monitored with a wide range of diagnostic instrumentation. In particular, diagnostics are used to monitor the plasma in the divertor areas to gain a better understanding of plasma flow, scrape-off layer (SOL) characteristics, impurity transport, baffle pressures, and heat flux reduction. Well over 50 diagnostics are utilized to measure the power balance, particle transport, erosion and sputtering of graphite, and gas density of divertor plasmas.

In the divertor, the surface temperatures of the components are measured with an array of six infrared cameras (IRTV's). The 8–12 μm light emission is recorded by the cameras and is used to infer the local heat flux on the divertor components. The radiative losses of the plasma are measured with two sets of bolometer arrays each with 24 viewing chords. The bolometer arrays provide complete poloidal coverage of both the divertor and core plasmas.

Plasma densities and temperatures in the divertors are provided by both fixed and moveable Langmuir probes and a Thomson scattering system (lower divertor only). Used in conjunction with infrared measurements, they directly measure the extent of the heat and particle flux reduction. Partial pressure measurements in the upper divertor are provided by ASDEX ionization gauges and modified Penning gauges.

Impurity concentrations in the plasma in the upper divertor are measured by a Tangential TV system which provides measurements from carbon (CII, CIII) and deuterium (D_α, D_β, D_γ). Also providing impurity measurements are filterscopes (interference filters and multi-chord) and a visible, high resolution multi-chord divertor spectrometer which measures line brightness and impurity ion temperature.

4. DIVERTOR STRUCTURES

For both of the upper divertors in DIII–D, the divertor structures are comprised of either two or three interconnected, toroidally continuous water-cooled panels. The water-cooled panels consist of either four 90° or three 120° sections that are pinned and welded together to form a continuous ring [4]. This structural design, though subjected to large toroidal currents during disruption, can accommodate the induced loads during the collapse of the plasma. The individual water panel sections are made from machined Inconel 625 plates which are spot and seam welded together to form a sandwich construction. For the upper outer and lower outer divertors, the space between the water-cooled panels and the vessel wall is bridged with radiatively cooled, Inconel 625 plates which serve to enclose the cryopump

The water-cooled panels are supported from the vessel walls and ceiling using brackets similar in design to those that support the cryopump. The brackets are flexible radially to allow for differential thermal expansion between the panels and the vessel during bakeout to 350°C, yet are vertically rigid so that they can withstand disruption loads.

5. TILES

Protecting all three divertors from the plasma heat flux are graphite tiles. These tiles are inertially cooled and are mechanically attached to the water panels and vessel using a stud clamping arrangement that has previously been described [5]. The thermal capabilities of the graphite tile design are 5 MW/m^2 for 5 s or 3.8 MW/m^2 for 10 s with a maximum surface temperature of 1500°C before ablation becomes a problem.

As part of the last installation phase of the RDP, the opportunity was taken to upgrade the thermal performance of the tiles. The motivation behind this upgrade was a desire to improve the operational time of the Thomson scattering diagnostic camera which was being saturated with light generated from overheated tile edges. Additionally, there was a desire to reduce carbon contamination of the plasma which was reaching 6% in high performance plasmas [6]. The upgrade was achieved by replacing facetted tiles on the top two rows of the centerpost with contoured tiles, by reducing the gaps between tiles from 2.5 mm to 1 mm at the strikepoint locations, and by minimizing the steps between adjacent tiles. The operational time of the Thomson system was also improved by the installation of high thermal conductivity, 3-D, carbon-carbon composite tiles.

6. OPERATIONAL RESULTS

The installation of the divertor equipment and instrumentation, discussed in the previous sections, into the DIII–D vacuum vessel has expanded the capabilities to investigate Advanced Tokamak (AT) scenarios. In these DIII–D AT scenarios the parameters relevant to the divertor are the core density and impurity concentration. The recently installed baffle, cryopump, and gas puff lines improve particle and density control while the new tighter tolerances on the upper strike point tiles reduce carbon contamination.

Density control of the core plasma is of particular interest to AT scenarios in that it directly influences the efficiency of rf current drive. Reducing the density increases this efficiency and increases the ability to deliver energy to the plasma. The addition of the inboard cryopump with a measured deuterium pumping speed of S_{in}= 20 k l/s (S_{out}= 37 k l/s) supplements the existing pumping capabilities. The ability to operate with either or both of the upper pumps has been demonstrated. Using both pumps, an AT target plasma of less than 0.35 times the Greenwald density has been maintained [7]. The effect of this increased pumping capability is shown in Fig. 2 which compares the minimum obtainable n_e near the edge containment barrier during ELMing H–mode for the three stages of upper divertor development.

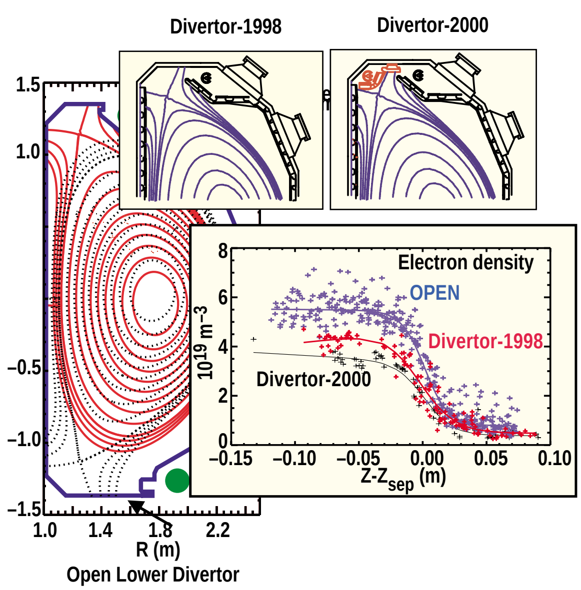

Fig. 2. A comparison of the three stages of divertor development of electron density (n_e). This is measured along a chord defined by the Thomson scattering diagnostic (Z) in the region of the edge confinement barrier during steady-state ELMing H–mode. Z_{sep} is the location of the magnetic separatrix.

Density and impurity control is also utilized in the divertor region to disperse the exhaust and reduce the heat flux to the walls. Using strong deuterium puffing (~300 Torr l/s) in conjunction with equal exhaust by the cryopump (puff and pump operation (P&P) [8]) reduction of the core impurity content and the heat flux on the divertor has been demonstrated [7]. Additional impurities have been introduced during P&P which have also enhanced radiation in the divertor thus reducing the heat flux.

Also important in the reduction of impurities in the plasma are the tighter tolerances which were incorporated into the upper strike point tiles. The expected decreases in tile edge heating [5] have been observed in recent experiments [9]. This can be seen in Fig. 3 which compares tile edge temperatures of the previously installed facetted tiles with large step and gaps with the new contoured tiles with smaller gaps and steps. Lower tile edge temperatures have also manifested themselves in lower plasma carbon contamination. A comparison of similar discharges before and after the improvements in tile design has shown a reduction of carbon content up to 50%.

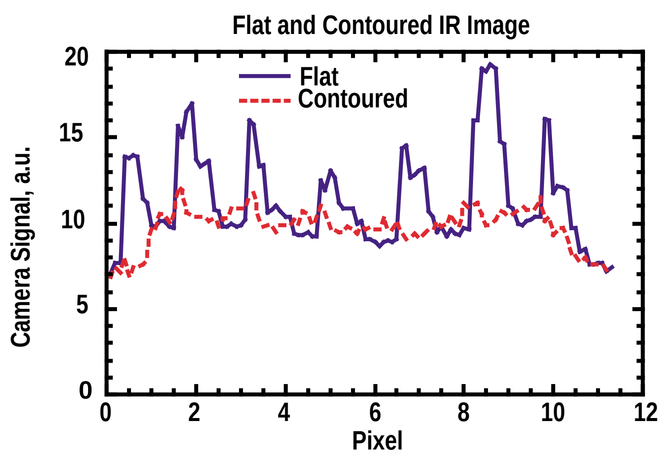

Fig. 3. Horizontal surface temperature profiles from IRTV images showing the variation between edge and surface temperatures for flat and contoured tiles.

7. SUMMARY

Following installation of the upper inner divertor, the RDP now has expanded capabilities in the research of particle transport, heat flux reduction and impurity control. The versatility of the divertor structures and cryopumps allows for active and independent control of pumping. Though the initial results have been very promising, many divertor experiments have yet to be performed to fully understand the physics of plasma flows, confinement and exhausts.

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