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Initial performance results of the DIII-D Divertor 2000

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Abstract

A major upgrade of the DIII-D divertor, with the goal of enhancing impurity and density control and increasing the thermal pulse length limit of advanced tokamak (AT) plasmas has been successfully completed and commissioned. The integrated system that includes independent cryopumps at both the inner and the outer legs of the divertor, private flux region and outboard baffles, and improved graphite divertor armor, has been successfully applied to a variety of plasma conditions. Comparison of similar discharges before and after the upgrades show that with the new divertor the core plasma neutral source and carbon content are lower by as much as 50%. Calculations supported by preliminary infrared (IR) camera measurements show that the new graphite armor design increases the limit on the discharge duration, due to temperature of the tile edges reaching sublimation point, by an order of magnitude. With the new system we have been able to control the density of high confinement H-mode plasmas to less than 1/3 of the Greenwald limit. It is observed that with divertor pumping during the current ramp phase the wall particle inventory and consequently the density rise after the H-mode transition can be significantly reduced.

Keywords: Divertor; DIII-D

1. Introduction

The new DIII-D Divertor, here referred to as DIVERTOR 2000, was designed with the primary goal of achieving density, impurity, and heat flux control in standard and AT plasmas. DIII-D AT scenarios require electron cyclotron (EC) current drive for steady-state operation and current profile optimization [1]. Since the current drive efficiency increases approximately linearly with the electron temperature and is inversely proportional to the electron density, for a given plasma pressure, the efficiency decreases quadratically with the local electron density. Therefore, the success of these scenarios critically depends on the ability to control the plasma density. However, low-density operation tends to aggravate the problems of radiative heat dispersal and

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impurity control. Thus one of the goals of DIVERTOR 2000 is to explore the viability of extending radiative heat dispersal and impurity control techniques to low-densities, prototypical of the AT plasmas. The divertor upgrades, shown in Fig. 1, include: a high-field side cryopump, a baffle structure in the private flux region (septum), and a new design for the inner wall graphite armor. The design and the results of experiments with the new divertor armor are described in Section 2.

The new pump is located at the inner upper corner of the DIII-D vessel and, together with the private flux baffle and the pre-existing low field side cryopump and baffle system, allows independent or simultaneous pumping of the divertor legs. The inner pump has a nominal pumping speed of 20 m^3/s, compared to 37 m^3/s for the outer upper divertor pump. The difference is primarily due to the smaller dimension of the inner pump aperture. In addition, because of geometrical constraints at the inside corner of the vessel, the baffle inlet aperture size and the conductance from the baffle inlet to the pump are also lower. Consequently the overall exhaust efficiency (defined in the following paragraph) of the inner pump is expected to be a factor of 3, lower than the two pre-existing divertor pumps. Otherwise, the design of the pump is similar to that of the outer pumps, which has been extensively described in earlier publications [2,3]. The primary purpose of the private flux baffle structure, shown in Fig. 1, is to shield the inner cryopump from the plasma. The baffle also reduces neutral recycling and thus contributes significantly to particle control [4,5]. A comparison of similar discharges with and without the private flux baffle shows nearly a factor of two reduction in core recycling [6]. The inner pump will serve three functions. It adds flexibility and enhances density control, serves as a tool for impurity control, and serves as a tool for widening the window for stable detached operation. Density control is described in Section 3. The topic of impurity control and stabilization of detached plasmas is discussed in Section 4.

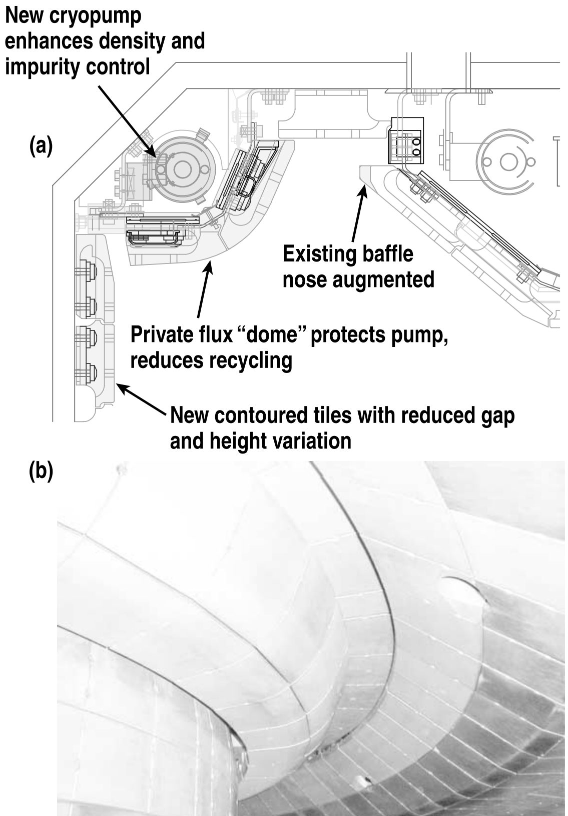

Fig. 1. (a) A cross-sectional view of the AT divertor. (b) A view of the upper divertor after the recent modification.

2. Divertor tile design and performance

The desire for long pulse low-density plasmas has significantly increased the heat handling requirements of the vessel armor. For this reason two rows of the DIII-D inner wall armor tiles located near the inner AT pumping plenum were modified to extend the pulse length of high performance plasmas. The original inner wall armor consisted of rows of flat plates with a spacing of up to 2.5 mm and height variation of <1 mm. The new tiles are contoured to the cylindrical shape of the inner wall, the spacing between the tiles is reduced to 0.62 mm, and the tile-to-tile height variation is limited to 0.1 mm. The reduced tile gap and height variation takes better advantage of the two-dimensional heat transport from the tile edges into the main body of the tile. In addition the rest of the tiles in the vicinity of the upper divertor strike points were sanded to reduce tile-to-tile height variation to 0.1 mm. Although parallel heat flux in the SOL of high powered long pulse DIII-D discharges appears to be sufficiently large to cause sublimation of tile edges, in practice with the exception of a few special discharges, no direct or indirect evidence of sublimation has been observed. This could be due to the mitigating effects of higher local radiation resulting from trapping of particles in tile gaps, motion of strike point position, and global radiative losses. In low-density AT plasmas the heating of tile edges can be significantly higher than in the standard H-mode discharges due to lower radiative heat dispersal and narrowing of the SOL. Furthermore, to enhance density control it is desirable to reduce the divertor flux expansion and fix the divertor strike point positions at the inlet of divertor pumps which further aggravates the problem. Fig. 2 shows results of a 2-D worst case thermal analysis of the new tiles compared with the old tiles. With a parallel heat load of 10 kW/cm^2, the edge temperature of old

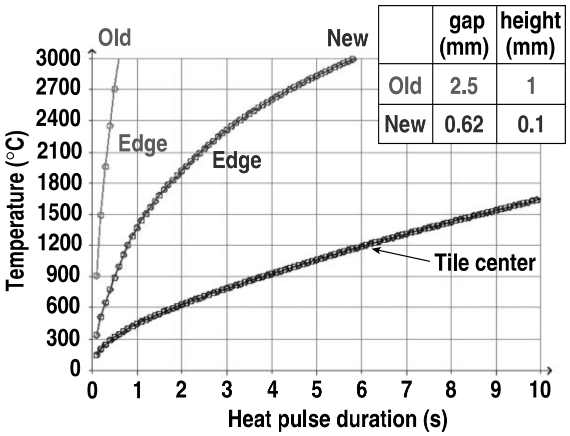

Fig. 2. Calculated temperatures of the edge and center of the ATJ graphite tiles for the new and the old design divertor target. The old tiles have a gap distance of 2.5 mm and a height variation of 1 mm. The new tiles have a maximum separation of 0.62 mm and a height variation of 0.1 mm. A parallel heat flux of 10 kW cm^{-2} and a field line angle of 2.5° relative to the center of the tiles was used for this calculation. The time to reach the sublimation temperature for the new tiles is an order of magnitude greater than that of the old tiles.

tiles reaches the sublimation point within 1 s; whereas the time to sublimation is increased to 6 s for the new tiles. IR camera measurements of adjacent old and new tiles [7] are in good qualitative agreement with the predictions of these calculations. A comparison of similar discharges before and after the modifications shows a significant reduction in carbon content of the low-density plasmas. It is not determined yet if the carbon reduction is due to the new geometry of the tiles or the effect of the new baffle structure.

3. Density control

In this section, we will present preliminary results on the application of the new divertor system on density control. To quantify the efficiency of the divertor pumping system for density control, we introduce the concept of particle exhaust efficiency. For the sake of simplicity in the following, unless explicitly stated, the effect of wall pumping is ignored and it is assumed that the external particle source is only due to the neutral beam injection (NBI). The Global exhaust efficiency, η_G, is defined as ratio of particle exhaust through all the pumping systems to the integral Γ_I, of the ion flux to all plasma facing surfaces. Similarly, the local pumping efficiency for each divertor pump, η_X, is defined as the ratio of exhaust through the pump to ion flux, integrated from the center of the private flux regions (point of closest approach to the X-point) to midplane. Defining f as the ratio of neutrals captured by the baffle to the ion flux, we can write $\eta = f[1 - 1/(1 + S/C)]$, where S is the pumping speed and C is the conductance of the baffle aperture. Since $S \approx C$, $\eta \approx 1/2\,f$.

The density profile roughly consists of two components; a pedestal that is determined by the recycling source, assuming no additional gas fuelling, and a sloped portion, from the pedestal to the center of the discharge, above this pedestal determined by the NBI particle source, and the particle transport parameters. Thus for a given NBI particle source and given particle transport parameters, the profile inside the pedestal radius should remain independent of divertor exhaust. With this simple picture in mind, we can see that divertor pumping to first-order only reduces the pedestal density. Similarly, since the baffle system reduces the probability of recycling neutrals reaching the separatrix, it also reduces the pedestal density. Since in equilibrium the pump exhaust rate equals the NBI particle source, as η_G increases the SOL density must decrease to reduce the divertor particle flux and maintain the same exhaust rate. Lowering of the divertor flux reduces the recyling source inside the separatrix thus reducing both the density gradient near the separatrix and the pedestal height in order to satisfy continuity. Thus η_G is a reasonable relative measure of the system capability for density control. Roughly, the pedestal density decreases with the square root of η_G. Fig. 3 shows the experimentally determined exhaust efficiency of the inner

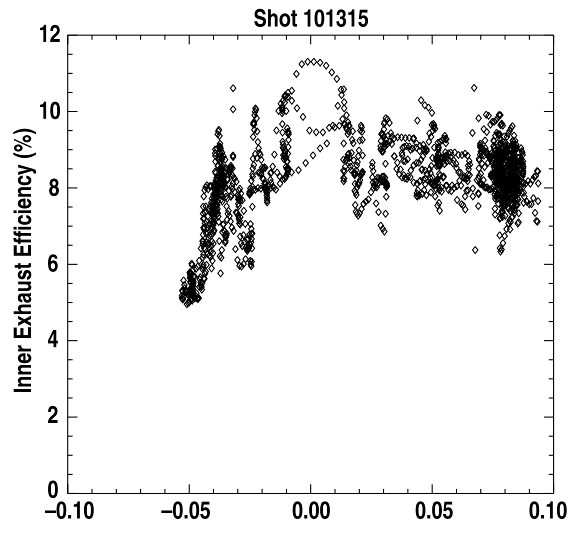

Fig. 3. Exhaust efficiency of the outer pump as a function of the strike point distance to the pump aperture. The exhaust efficiency increases sharply when the separatrix distance from the pump aperture is less than the SOL width.

divertor pump as a function of the strike point distance to the outer pump aperture, for a single-null plasma. As expected η_{inner} reaches its peak when strike point position is less than one SOL width away form the pump aperture [2,8–11]. For the determination of η, divertor ion flux was measured by an array of Langmuir probes imbedded in the divertor plates [11] and the pump exhaust was determined by measuring neutral pressure under the baffles by ASDEX gauges located in the pumping plenums and results of in situ calibration of the pumping speeds. The exhaust efficiency of the outer pump, η_{outer}, displays a similar behavior with the inner strike point position, but as explained above it is roughly $\simeq 3\ \eta_{inner}$. The exhaust efficiency of both pumps increase with decreasing flux expansion. These general features of measured exhaust efficiencies can be reproduced by simple geometrical constructions [2,10,11]; however the details, particularly at high density, cannot be explained by geometry alone. A discussion of the detailed behavior of the exhaust efficiency is beyond the scope of this paper and will be presented elsewhere [11].

Double-null (DN) plasma shapes have been found to have superior confinement and stability characteristics compared to the single-null (SN). For this reason, currently all the DIII-D AT plasmas scenarios are based on the DN shapes. Since presently only the top half of the vessel is equipped with pumps and baffle structures, pumping of DN shapes is not as effective as the SN [5]. A compromise was found by using a DN shape that is slightly biased to the top, such that DRSEP, defined as the distance between the upper and lower null separatrix at midplane, was, $\sim$0.5 cm [12]. With this configuration, as shown in Fig. 4, shot 101916, density decayed to 1/3 of the Greenwald limit at 4.5 s into the discharge time.

Up to this point we have neglected the effect of wall particle source in our discussion. This is normally a good assumption only several seconds after the equilibrium has been disturbed. We have demonstrated in

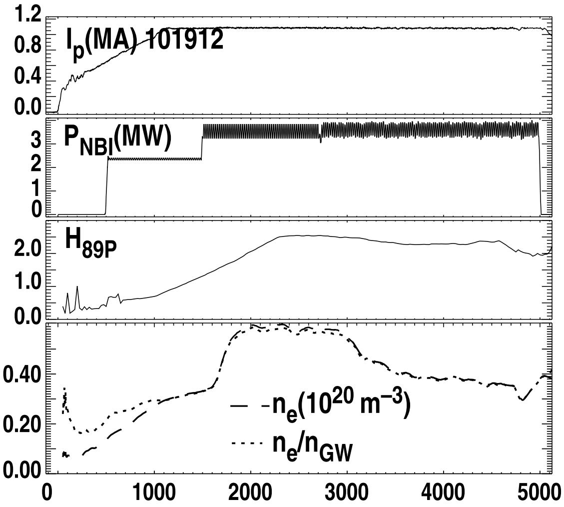

Fig. 4. Density decay of a high confinement double-null H-mode plasma with divertor pumping. The configuration was slightly biased towards the upper pump, with DRSEP $\sim$ 0.5 cm. Density decays to 1/3 of the Greenwald limit after two seconds of strong pumping.

the past [13,14] that with divertor pumping the wall particle inventory at the end of the discharge can be reduced to, or even below, its value at the start of the discharge. However, normally during the discharge initiation and current ramp-up the wall particle load increases by several times the desired particle inventory of the H-mode plasmas. The release of some of these particles during the H-mode transition results in a rapid density rise following the transition (the rate of this density rise is normally much higher than the external particle sources). In order to reduce this density rise we studied the effect of pumping during the current ramp-up on the wall particle inventory. The results displayed in Fig. 5 show that both the wall particle inventory and

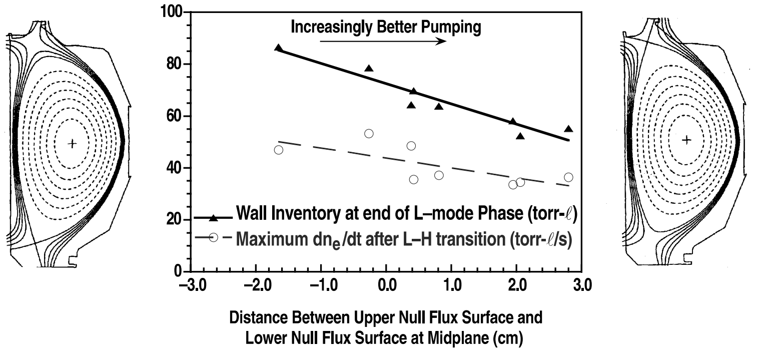

Fig. 5. The wall particle inventory and the rate of density rise after the H-mode transition are reduced by divertor pumping during the current ramp phase of the discharge. Pumping rate is varied by varying the magnetic balance from lower SN (low pumping) to upper SN (high pumping).

the rate of density rise after the H-mode transition are reduced significantly with increasing pumping during the current ramp up phase. For this experiment the pumping rate was varied shot by shot by changing the magnetic balance from lower SN, for weak, to upper SN, for strong pumping. These observations suggest an operating scenario where during the current ramp-up phase, the configuration is maintained in the upper SN shape to reduce the wall particle source after the H-mode transitions, then after the transition, the plasma shape is changed to the DN shape for optimum confinement and stability.

4. Impurity control and stabilization of detached plasmas

Earlier experiments on DIII-D [15,16] have shown the importance of SOL flows for divertor impurity enrichment and achieving densities above the Greenwald limit. A flow can be generated by simultaneous divertor pumping and gas fueling away from the divertor. A flow of the working gas particles towards the divertor target can effectively entrain impurities only if the collisional drag force on the impurity ions exceeds the ion temperature gradient force driving impurities upstream. The ion temperature gradient force is expected to be higher in low-density plasmas. This is due to the fact that at low collisionality electrons and ions are decoupled and thus ∇T_i is solely determined by the ion thermal conductivity; whereas, at high collisionality when ions and electrons are in thermal equilibrium in the SOL, ∇T_i is determined by the much larger electron heat conductivity. Therefore, a greater flow speed would be required for divertor impurity enrichment in low-density plasmas. The second divertor pump combined with improved baffles should allow a greater and a more balanced SOL flow. We plan to use this extended capability for developing impurity control and divertor impurity enrichment for radiative cooling of the AT plasmas. Preliminary results using the new system are encouraging [17]. In H-mode plasmas at densities as low as 0.5 Greenwald limit concentrations of argon and neon were reduced by factors of 5 and 2, respectively, when the gas injection source was shifted from the private flux region (no upstream flow) to the bottom of the vessel.

5. Summary

The DIII-D divertor system has been upgraded for more effective particle, heat and impurity control. The integrated system which includes independent cryopumps at inner and outer legs of the divertor, private flux and outboard baffle systems, and improved graphite armor in the high-heat load areas, has been successfully applied to a variety of plasma shapes and conditions. Calculations and initial camera measurement show that the new inner wall tile design increases the discharge duration limit due to heating of the tile edges by an order of magnitude. With the new system density control of high performance H-mode plasmas is achieved. It is observed that with pumping during the current ramp phase, the wall particle inventory and consequently density rise after H-mode transition is reduced.

Acknowledgements

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