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EFFECT OF LOW DENSITY H-MODE OPERATION ON EDGE AND DIVERTOR PLASMA PARAMETERS

by

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ABSTRACT

We present a study of the impact of H-mode operation at low density on divertor plasma parameters on the DIII-D tokamak. The line-average density in H-mode was scanned by variation of the particle exhaust rate, using the recently installed divertor cryo-condensation pump. The maximum decrease (50%) in line-average electron density was accompanied by a factor of 2 increase in the edge electron temperature, and 10% and 20% reductions in the measured core and divertor radiated power, respectively. The measured total power to the inboard divertor target increased by a factor of 3, with the major contribution coming from a factor of 5 increase in the peak heat flux very close to the inner strike point. The measured increase in power at the inboard divertor target was approximately equal to the measured decrease in core and divertor radiation.

1. INTRODUCTION

In this paper we examine the effect of divertor pumping on the divertor plasma conditions in the DIII-D tokamak. Divertor pumping has been used to study helium removal and to lower the density of H-mode plasmas in order to improve non-inductive current drive efficiency. However reducing the H-mode plasma density may increase the limiter/divertor target erosion due to the increased temperature. At a fixed input power and high recycling conditions, it has been shown (Mahdavi [1]) that the divertor plasma density scales as a cube of the line average density ($\bar{n}_e$) and the divertor electron temperature as $\bar{n}_e^{-2}$. In this case, a small reduction in the H-mode line average density can result in a large reduction in the divertor target particle flux ($\sim nT^{1/2}$), but should produce little change in the heat flux ($\sim nT^{3/2}$). This model, however, neglects the density dependence of the radial energy transport, $n\chi\nabla T$, which can produce a narrower scrape-off layer (SOL) plasma and higher peak heat flux at lower density. Also, lower SOL density results in lower radiative losses [$\propto n_en_iL(T)$] and more power conducted to the target plates. Previously, it was found that the inner divertor heat flux increased as the line-average density was reduced in ohmic discharges (Hill [2]).

Without a means to control the particle exhaust, density control in H-mode operation has not been possible because the line-average density generally clamps to a fixed multiple of the plasma current. Somewhat higher density can be achieved by gas puffing, but often at the expense of the quality of the H-mode confinement. Use of an in-vessel cryopump installed in 1993 in the DIII-D tokamak (Smith [3]) has allowed variation of the H-mode line-average density by more than a factor of 2 (Mahdavi [4]).

2. EXPERIMENT

To examine the effect of low density operation on divertor particle and power flow, the line-average electron density (as measured by an interferometer) was scanned over a range between 3×10^{13} and $6 \times 10^{13} \text{ cm}^{-3}$ at a plasma current of 1.0 MA in a lower, single-null diverted configuration. The neutral beam injection power was fixed at 5 MW during this scan, resulting in ELMing H-mode discharges (ELM frequency ~ 50 Hz for the high density discharges). The toroidal field was fixed at 2.1 T, and the ion grad-B drift was toward the x-point.

The DIII-D advanced divertor includes a toroidally symmetric biasing ring and baffle, which create a pumping plenum for the recently installed in-vessel helium cryogenic condensation pump (Fig. 1). The density scan was accomplished by varying the separatrix-ring gap, the minimum distance between the outer leg of the separatrix and the edge of the biasing ring, *i.e.* the entrance to the pump plenum. Previous experiments have shown that the neutral pressure in the pump plenum is a strong function of this separatrix-ring gap (Klepper [5]). In this experiment, it was determined that the cryopump particle exhaust rate also has a strong dependence on the separatrix-ring gap, as expected (Fig. 2). The exhaust rate is estimated as the product of the D₂ pumping speed (measured in off-line tests) and the pump plenum neutral pressure with the cryopump on. This strong dependence shown in Fig. 2 was used to change the exhaust rate on a shot-to-shot basis. In this paper, high-density refers to the unpumped H-mode density ($5.2 \times 10^{13} \text{ cm}^{-3}$).

During this experiment, edge electron density and temperature above the outer midplane were measured by the Thomson scattering diagnostic; ion temperature at the outer midplane was measured by charge-exchange-recombination spectroscopy; heat flux deposition across the entire divertor floor was measured by an infrared television camera (IRTV); radiated power was measured by a bolometer array; D α emission was measured by calibrated filtered photomultipliers; and divertor floor electron density and temperature were measured at discreet

locations by Langmuir probes (Fig. 1). In addition, neutral pressure from fast time response ionization gauges was measured in the private flux region and in the pumping plenum. Line-average density was measured with an interferometer; the line-of sight of the selected interferometer chord passed near the center of the plasma. Almost all of the divertor floor was observed by the divertor diagnostics during the outer strike point (OSP) sweeps, except at the time of maximum particle exhaust. At these times, the OSP was shadowed by the biasing ring so that the heat flux could not be measured. Moreover, the outermost divertor Langmuir probe is located ~ 6 cm radially inward of the OSP radial location during maximum particle exhaust, preventing the examination of particle flux, electron density and temperature during the time of maximum particle exhaust. Nevertheless the power balance on the inner divertor leg can be examined.

Fig. 1. Schematic representation of the DIII-D magnetic flux surface geometry and bias ring/pumping plenum, and the separatrix-ring gap.

3. DATA

Density scans in H-mode discharges have shown that the wall history can affect the density reduction obtained from standard H-mode values, even when operating at the OSP location of maximum particle exhaust; *i.e.*, it takes several (4–5) shots with maximum particle exhaust to obtain the lowest line-average density (Maingi [6]). This wall hysteresis effect is also present in the data shown in this paper, so that the measured line-average density does not scale directly with the particle exhaust rate. However, the magnitude of this effect has been reduced as compared to previously reported hysteresis data so that only 2–3 shots are required for maximum reduction in line-average density, due to elimination of the deuterium gas from the helium glow discharge cleaning procedure (Mahdavi [4]).

Fig. 2. Measured particle exhaust rate vs. separatrix-ring gap distance. Variation of the separatrix-ring gap was accomplished by a slow, continuous sweep of the OSP, starting far away from the pumping plenum and ending with the OSP under the biasing ring, well inside the pump plenum. The line-average electron density was reduced from 5×10^{13} to $4 \times 10^{13} \text{ cm}^{-3}$ during the gap scan.

Table I shows a comparison of plasma parameters for three different line-average densities: high density, unpumped H-mode (5.2×10^{13}), mid-density H-mode with modest pumping (4.7×10^{13}), in which both the inner and outer divertor target parameters can be measured, and low density H-mode with maximum pumping (3×10^{13}), in which only the inner divertor target parameters can be measured. The ion saturation currents quoted in Table I are obtained by integrating the divertor target particle flux profile, measured by Langmuir probes. The analysis technique for the Langmuir probe data effectively screens out ELMs, so that the value quoted is actually the current between ELMs. The infrared television camera (IRTV) heat flux, D_α emission, and the private-flux region neutral pressure are also measured between ELMs, whereas the other data is averaged over ELMs. The following discussion is broken up into two parts: the dependence of peak divertor heat flux and particle flux on density, and the dependence of the radiation/heat flux balance on density.

Table I
Summary of Measured Edge and Divertor Plasma Parameters from Density Scan

n_e line-average (cm^{-3})	5.2×10^{13}	4.7×10^{13}	3.0×10^{13}
Particle exhaust rate (A)	0	110	165
D_α (inner divertor target) ($\text{cm}^{-2}\text{s}^{-1}\text{ster}^{-1}$)	1.5×10^{16}	4.1×10^{15}	3.0×10^{15}
D_α (outer divertor target) ($\text{cm}^{-2}\text{s}^{-1}\text{ster}^{-1}$)	1.2×10^{16}	5.6×10^{15}	
Private flux region neutral pressure (mTorr)	0.75	0.57	0.35
n_e (outer midplane separatrix) (cm^{-3})	1.3×10^{13}	1.1×10^{13}	0.80×10^{13}
T_e (outer midplane separatrix) (eV)	130	150	225
$n_e T_e$ (outer midplane separatrix) (Pa)	270	264	290
Ion current (inner divertor) (A)	1000 (2200)*	3000 (1200)	1000 (1100)
Ion current (outer divertor) (A)	6000 (12,800)	3000 (2900)	(1430)
Radiated power (core) (kW)	1100	900	800
SOL power (kW)	2350 [†] (2150)	2900 [†] (2750)	(2940)
Inner divertor radiated power (kW)	800 (800)	1000 (960)	650 (600)
Outer divertor radiated power (kW)	250 (290)	250 (220)	(90)
Inner divertor target power (kW)	300 (310)	400 (390)	1000 (600)
Outer divertor target power (kW)	1000 (1000)	1200 (1210)	(1370)
Inner divertor peak heat flux (W/cm^2)	20 (35)	50 (40)	100 (200)
Outer divertor peak heat flux (W/cm^2)	120 (350)	170 (490)	

*Simulated values in parentheses

[†]Value inferred from sum of divertor radiated power and target power, for comparison.

3.1. Particle Flux And Heat Flux Data

The first salient feature evident in Table I is that the inner divertor ion saturation current does not decrease monotonically as the line-average density is reduced, even though the power and heat flux increase monotonically. The peaking of the ion saturation current for the mid-density data is consistent with the increase in divertor radiation. This observation of non-monotonic dependence on density can also be seen in the particle flux data. Figure 3(a) displays the peak measured particle flux and heat flux at the inner target as a function of line-average density. It is clear from this figure that the inner target particle flux peaks for the mid-density case (4.7×10^{13}), and decreases at both lower and higher density. The peak heat flux on the other hand, monotonically increases as the line average density is reduced. Figure 3(b) displays the corresponding peak particle and heat flux measured at the outboard target as a function of density. Note that the outboard parameters at the lowest densities could not be measured. Although the data set is small, the outboard target particle flux does decrease as the density is reduced, and the heat flux increases. Thus, the density dependence of the outboard target parameters is qualitatively similar to the inboard target parameters below 4.7×10^{13} , *i.e.* the particle flux decreases and the heat flux increases as the density is reduced. However the simultaneous decrease of particle flux and heat flux at the inboard target above 4.7×10^{13} suggests a change in the physics governing the relationship between the two. This behavior has also been observed along the outboard target during strong deuterium gas injection on the DIII-D tokamak, when the plasma along the separatrix was in a detached state (Petrie [7]). In that experiment, the plasma farther out in the SOL was not detached. A recent model has hypothesized that a strong momentum transfer to recycled neutrals via charge exchange causes a loss of pressure balance along the separatrix at sufficiently high neutral pressure, leading to this detached state (Ghendrih [8]). This model specifically addresses transition of the outboard divertor to a detached state, but the basic physics can be applied to the inboard divertor as well. If detachment actually does occur along the separatrix (due to a loss of plasma momentum), a reduction in the separatrix heat flux is expected. However the heat flux far away from the

separatrix may not be reduced, thus leading to a very broad heat flux profile. Figures 4(a) and 4(b) display the inner and outer target heat flux profiles for the high and mid-density discharges. Note that for the mid-density case, the heat flux profiles at the targets are both strongly peaked at the strike points to within the resolution of the magnetic mapping. For the high density case, however, the inner target heat flux profile is very broad and peaks well away from the strike point. Thus, it can be inferred that the inner target plasma is in a detached state. Apparently the unpumped H-mode operation at the specified density and input power level leads to a detachment of the inboard divertor without strong gas injection, thereby allowing simultaneous reduction of particle flux and heat flux (as compared with the mid-density case).

Fig. 3. Comparison of peak particle and heat flux profiles as a function of line-average density at the (a) inner and (b) outer divertor target. The circles represent the particle flux data, and the x's represent the heat flux data.

3.2. Radiation And Heat Flux Balance

The other interesting feature in Table I is the measured reduction in divertor and core radiated power, ostensibly caused by reduced electron and neutral particle inventory. An important consequence of the reduced core radiation is that the power crossing the separatrix into the SOL must increase. This extra power in the SOL shows up at the divertor target plates. It is very interesting to note that the increase in inboard power measured by the IRTV exceeds the drop in inboard divertor radiation. Figure 5 shows that this inboard target power increase is roughly equal to the decrease in total radiation (sum of core, inboard and outboard divertor). If the total SOL power has remained fixed in going from mid to low density (core radiation changed only by 10%), then this observation implies that there is little change in power to the outboard target, and so the in/out power split ratio increases as the density is reduced. The conclusion is preliminary, however, because the radiated power data was measured by a bolometer array which did not have overlapping views, thus preventing precise separation of core and SOL radiation above the X-point. In addition, this set of discharges had only about 75% input power accountability on average. It is very possible that the unaccountable power loss has a density dependence, such that the above assumption of similar power flow is a dubious one.

Fig. 4. Comparison of inner/outer divertor target heat flux profiles for the (a) high and (b) mid-density discharges, as a function of normalized magnetic flux, Ψ_n . Here $\Psi_n(r, z) \equiv [\Psi_c - \Psi(r, z)] / (\Psi_c - \Psi_{sep})$, where Ψ_c is magnetic flux at the plasma center, and Ψ_{sep} is the magnetic flux at the separatrix, $\Psi_n = 1.0$ is the separatrix. The nominal uncertainty of the separatrix location is $\Psi_n = \pm 0.01$.

4. 2-D EDGE PLASMA TRANSPORT ANALYSIS

To understand the changes in the particle and power flow during low density operation, data at three different line-average density were simulated with a 2-D edge plasma transport code. The main objectives of the simulations were: 1) to determine the cause of the observed heat flux peaking; and 2) to determine if the in/out power flow ratio is affected by the radiation/heat flux tradeoff. The b2.5 edge plasma transport code was used for this purpose (Braams [9]). In this code, the parallel ion and electron transport is classical, except that kinetic limits on parallel electron conduction, ion conduction, and momentum transport are simulated by the use of free-streaming coefficients. Transport across magnetic field lines is anomalous with fixed transport coefficients. The neutral transport is done with a semi-analytic multiple-energy species model which considers the transport of molecules, Franck-Condots, and fast reflected atoms, and contains an approximation for charge exchange neutrals. This neutral transport model has been compared with coupled b2/DEGAS calculations for identical problems, and the agreement between the two models was very good over a wide range of input parameters (Maingi [10]).

Several free parameters in the simulations were determined by comparison with data for the high density case. These parameters were held fixed for the low and mid-density simulations. Specifically, the perpendicular transport coefficients $(\chi_{\perp}^e, \chi_{\perp}^i, D_{\perp})$ were determined by fitting the measured profiles for upstream electron density and temperature (Thomson scattering) and ion temperature (CER). The pinch velocity, v_{pinch} , was determined by comparison with divertor floor Langmuir probe ion saturation current profiles. For these simulations, the following values provided a reasonable match to the measured profiles: $\chi_{\perp}^e = 0.35 \text{ m}^2/\text{s}$, $\chi_{\perp}^i = 0.25 \text{ m}^2/\text{s}$, $D_{\perp} = 0.15 \text{ m}^2/\text{s}$, $v_{\text{pinch}} = -10 \text{ m/s}$.

Simulation of the low and mid-density cases was accomplished by (1) variation of the boundary values for plasma density and temperatures as necessary to match the data, (2) variation of the plate recycling coefficient to simulate the effect of pumping, and (3) variation

of the divertor radiation. The boundary values were prescribed at the 98% normalized magnetic flux surface ($\Psi_n = 0.98$, just inside the separatrix). The plate recycling coefficients for the three cases were determined by comparison of the measured cryopump exhaust rate with the calculated particle removal at the target plates. The values of the plate recycling coefficient which was used in these simulations were: 1.0 (high density), 0.975 (mid-density), and 0.965 (low density). The outer wall recycling coefficient was fixed at 0.9 for all of the simulations. Impurity radiation was simulated by enhancement of the hydrogenic radiation component, which was determined by comparison with the measured divertor radiation. The required enhancement factor was higher for the inboard divertor leg than the outboard leg, and was determined separately at each density.

Fig. 5. Measured radiation/heat target power dependence on line-average density. The circles represent the power measured at the inner divertor target, and the triangles represent the measured radiation. Note that the reduction in radiation is roughly equal to the increase in inner target power.

The magnetic equilibrium was generated by the EFITD code (Lao [11]); because this equilibrium is generally accurate to within 0.5 cm at the outer midplane in the determination of the separatrix location, the separatrix location was adjusted when necessary to ensure the correct SOL power flow. For these simulations, the SOL power flow was varied until the power

deposited at the inner and outer divertor target, including radiation heat flux, was equal to the total measured target power. Note that the total target power was effectively an input constraint, and that the power to each target separately was determined by the model, allowing the investigation of the in/out power ratio. For the lowest line-average density simulation when the outer divertor target power could not be measured, it was assumed that the SOL power flow was such that the target power was equal to the value for the mid-density case plus the measured reduction in the core radiated power.

A comparison between the simulation results and measured data is presented in Table 1. The calculations qualitatively reproduce the trend of increasing peak heat flux at the inner and outer targets with decreasing density. Table 2 shows the various components of the calculated peak heat flux. Note that the peaking of the heat flux appears to be caused primarily by an increase in electron conduction power which actually makes it to the target along the separatrix, and that electron convection is also enhanced. The basic point is that even at high density, most of the power flowing in the inner leg is concentrated close to the separatrix, but that this power gets dissipated by strong radiative losses. As evident in Table 2, the target plate peak heat flux consists mainly of radiation and recombination for the high density case. However, as the density is reduced, the electron temperature at the target increases somewhat, allowing a strong electron conduction and convection component to the target. On the issue of in/out power, the simulations indicate that this ratio increases only slightly with decreasing radiation, much less than the increase inferred in 3.2. In other words, the simulations indicate that a significant fraction of the reduction in radiated power at reduced density should appear at the outboard target as heat flux, contrary to the observation that all of radiation decrease appears at the inboard target as heat flux.

It should be noted that various simulation attempts at the lowest density failed to accurately match the measured inner target power for the prescribed constraint on SOL power, *i.e.* it would take significantly more power in the SOL to match this data. Also, the model does not reproduce the drop in particle flux observed at the inner divertor for the high density, detached plasma case. Because the computed particle flux at the inner target is too high, the recombination part of the

peak heat flux is also too high, which explains the reason that the model peak heat flux is higher than the data for that case. The probable reason for the discrepancy in matching the particle flux is the inadequacy of the charge exchange (CX) approximation in the multi-species neutral transport model. This CX model reasonably approximates the global energy loss from CX events, but not the momentum loss. Coupling of the multi-species neutral transport model to the CX fluid model offered in the b2.5 code is underway. In general the simulated target ion currents are in poor agreement with the measured data, which is probably caused by the sheath power boundary condition used in the simulations. Here we have used collisionless sheath power transmission coefficients; anomalous values have been reported from DIII-D and it has been hypothesized that collisions within the magnetic sheath can reduce these coefficients (Futch [12]), and the presence of non-ambipolar flow can increase these coefficients (Cuthbertson [13]).

Table 2
Components of Inboard Divertor Heat Flux From Simulations

n_e line-average (cm^{-3})	5.2×10^{13}	4.7×10^{13}	3.0×10^{13}
Total peak heat flux (W/cm^2)	35	40	196
Electron conduction heat flux (W/cm^2)	3.0	7.3	90
Electron convection heat flux (W/cm^2)	1.5	2.6	55
Ion conduction heat flux (W/cm^2)	<0.1	<0.1	0.3
Ion convection heat flux (W/cm^2)	4.5	5.4	18
Radiation heat flux (W/cm^2)	14.4	14.2	27
Recombination heat flux (W/cm^2)	14.2	9.5	5.7

5. CONCLUSIONS

It has been shown that the peak heat flux increases and peak particle flux decreases at the inner and outer divertor targets as the line-average density is increased. Above a critical density, however, both the peak heat flux and particle flux at the inner divertor decrease with increasing density, suggesting a loss of pressure balance, *i.e.* a detached state. This decoupling of the inverse relationship between peak heat flux and particle flux was not observed at the outer divertor target during this experiment, although it has been reported at higher density than examined here (Petrie [7]). It has also been shown that as the density is reduced in H-mode discharges, a reduction in the radiated power is observed, and that roughly all of this reduction shows up on the inner divertor target as heat flux.

Two-dimensional simulations indicate that the increase in peak flux at the inner target occurs because the decrease in radiation allows a connection of electron conduction and convection power to the target. In addition, the simulations indicate that no increase in the in/out power ratio is expected as the density is reduced. The experimental investigation of the in/out power balance as a function of density was limited by the inability to measure the outer target heat flux, density, and temperature at the lowest density. This limitation will be eliminated during the upcoming experimental campaign, when a measurement of the power balance at the lowest density will be facilitated with a new IRTV camera viewing into the pump plenum. In addition, a recently installed bolometer array will allow for 2-D tomographic reconstruction of radiated power profiles (Leonard [14]).

The implication for future machines that require low density operation is that the inner divertor leg may carry a non-negligible fraction of the total injected power, contrary to the assumption commonly used in present design studies. Hence plasma facing surfaces along the inner leg (in a lower single-null divertor configuration) should be designed for comparable heat loads as the outer divertor leg. Power flow symmetry (where the flow in the inboard divertor

channel is closer in magnitude to the flow in the outboard channel) may accompany low density operation, the possible benefit of which may be reduced radiated power requirements from the outboard divertor leg.

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