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Journal of Nuclear Materials 266–269 (1999) 739–741

journal of nuclear materials

# Effect of divertor geometry on plasma detachment in DIII-D

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**Abstract**

UEDGE simulation of the radiative divertor plasma (RDP) (nearly closed divertor) in DIII-D indicates a 40% reduction in the core density necessary for fully detached pure deuterium plasmas at 3 MW core power. Including intrinsic carbon impurities to the UEDGE model expands the region for fully detached plasmas and further reduces the necessary core density for this state. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* UEDGE; Radiative divertor; Deuterium; Detached plasma

## 1. Introduction

This paper explores the physics of the recently installed radiative divertor plasma (RDP) divertor in DIII-D through the use of UEDGE simulation with experimentally derived plasma parameters. The RDP is a nearly closed baffle and cryopumping system in the upper divertor of DIII-D [1]. One measure of the effectiveness of the RDP is the achievement of a detached plasma with a lower core density than in the open divertor (present in the lower divertor in DIII-D). Plasma detachment, observed on all diverted tokamaks, is a change in the plasma state which results in a decrease in both the ion current and heat load on the divertor plate. These reductions together with the related drop in electron temperature are important for divertor design in high power devices such as ITER, in which detached operation is assumed [2]. Both UEDGE modeling and DIII-D experiments show a reduction of 25–50% in the core density necessary for plasma detachment in the RDP compared to the open divertor.

## 2. UEDGE modeling of detachment window in deuterium for open and RDP divertors

The core density and SOL heating power operating range for detached in the open, lower divertor of DIII-D was examined by Porter using UEDGE, a 2-D, hydrogenic fluid code that includes parallel momentum exchange between ions and neutrals via charge exchange in the SOL and divertor region [3]. His technique was essentially the same as in this paper, which investigates the (nearly) closed RDP. The geometry of the RDP case is fixed as the upper single null shot 92 044 at 3750 ms. Because of the poor diagnostics in the upper divertor, we have used transport coefficients from the best fit to a similar discharge run in the lower divertor, 86 586 at 2500 ms, for which the lower divertor detachment window was determined. Fixed anomalous perpendicular diffusion coefficients were used in simulations for the lower and upper divertors, namely for the density, $D_\perp = 0.3$ m$^2$/s, and for the electron heat diffusivity, kye = kyi = 1.5 m$^2$/s. The walls remove 5% of incident neutrals and the baffle pumping was simulated by removing 5% of the ions impinging on the cells corresponding to the entance to the RDP baffle. These input parameters were then fixed in UEDGE, and the response of the plasma to changes in the core density and SOL heating power was examined initially for no impurities. The comparison of results for the open and closed divertors is summarized in Fig. 1.

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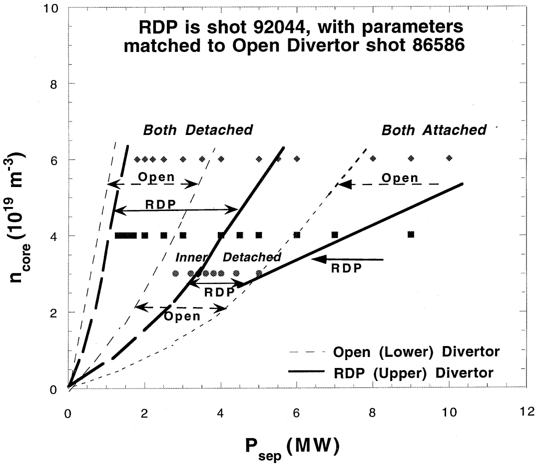

Fig. 1. UEDGE simulation of the detachment window for SOL plasmas in pure deuterium for open and RDP divertors in DIII-D.

One finds that the plasma is attached at both the inner and outer plates of the open divertor if the heating power is sufficiently high, regardless of upstream density. However, in the closed divertor we have not obtained attachment on the inside for heating powers up to 12 MW. For the open divertor, if the power is reduced, at fixed density, the inner plate plasma detaches while the outer remains attached. Detachment is defined here as a reduction of the plate temperature (at the UEDGE cell just above the strike point) below that required for efficient reionization of the recycling gas, about 5 eV. This detachment boundary does not necessarily correspond to that at which one finds dramatic reduction in the plate ion current, but we find the reduction of the plate temperature to be the first step in the detachment process.

For both the open and closed divertors, we then observe a range of heating powers at which the plasma remains detached on the inside and attached on the outside. The ionization front (defined to be at an electron temperature of 5 eV) moves up the inner leg towards the X-point as the power is reduced. This movement of the ionization front expands the region with very low electron temperatures. The electron temperature below this ionization front is found to be fairly constant, between 1 and 2 eV. In DIII-D experiments, large regions with such low temperatures have been measured in the open divertor using the divertor Thomson scattering system (available only for the lower divertor) [4].

The next phase of detached operation occurs for both divertors when the ionization front on the inner leg reaches the X-point. Further reduction in the heating power leads to detachment at the outer leg. The ionization front on the outer leg then moves up the separatrix, while it remains just below the X-point on the inside, as the heating power is reduced further. This is the optimum operating regime in which the heat load to either divertor is reduced on both the inner and outer legs. Note that for 3 MW power for example, the core density necessary to cross this boundary is reduced from $4.5 \times 10^{19}$ in the open divertor to $2.7 \times 10^{19}$ in the RDP, a 40% decrease. This may be compared to recent DIII-D measurements that show a reduction of more than 20% [5].

The final phase of detached operation is reached when the ionization front on the outside lies just below the X-point. In this state the electron temperature is between 1 and 2 eV everywhere below the X-point and therefore neutrals, which arise from recycling at the divertor, can penetrate to the closed flux surfaces. Further reduction of the heating power leads to the core MARFE state, in which the ionization front moves above the X-point, both inside and outside. A localized high density, low temperature region forms on the closed flux surfaces just above the X-point on the inside. This region has sufficiently high density to radiate large amounts of power, even in the pure deuterium plasmas we have modeled.

Each of these plasma states is also seen experimentally. One always sees detached plasmas first on the inside, in fact it is rather difficult to avoid detachment there. The outer leg is usually detached by enhancing radiative losses with the injection of either deuterium or other gas puffing, or from sputtered carbon. Outer detachment is also seen in low power Ohmic operation. Finally, when too much gas has been injected, the core MARFE is accompanied by reduced core confinement and occasionally disruption. The similarity between these observed plasma states and those seen in the UEDGE simulation lends credence to the SOL physics models.

## 3. UEDGE modeling of the detachment window in the RDP divertor with impurities

Our UEDGE calculations explored the effect of the intrinsic carbon impurity, introduced by sputtering from the walls of DIII-D, on the RDP detachment window, assuming a fixed sputtering coefficient on all surfaces in the device. We assumed that the private flux and outer walls are a source of carbon via chemical sputtering in which a low energy deuterium neutral or ion is chemically absorbed on the surface and then emerges as a volatile hydrocarbon. This molecule is subsequently dissociated in the plasma, thus introducing carbon. The same process exists in the divertor region which is, however, subject to intense deuterium ion flux near the strike points. Although bombardment with ions from an attached plasma can reach several hundred eVs, leading

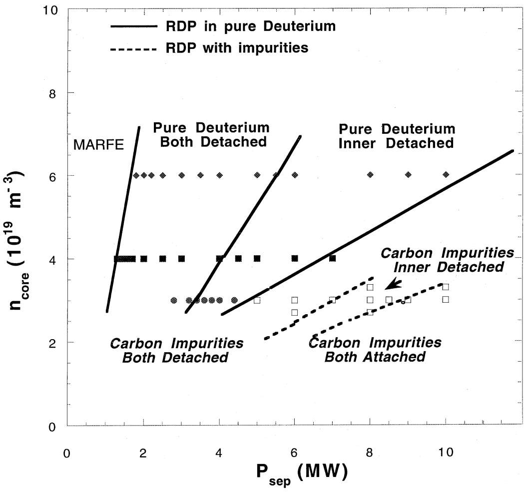

Fig. 2. UEDGE simulation of the RDP detachment window for SOL plasmas with and without impurities.

to higher carbon yields, the carbon sputtering for these processes is a currently an active research field. Therefore a sputtering coefficient of $Y = 0.005$ was chosen to agree with upstream plasma values of total radiation in DIII-D experiments.

To explore the RDP detachment boundaries with impurities we scanned the core power from 5 to 10 MW for a fixed value of core density, namely $3.0 \times 10^{19}$ $m^{-3}$. The results are shown in Fig. 2, which presents a comparison to an RDP scan in pure deuterium. It can be seen that the intrinsic carbon impurities expand the region for a fully detached plasma and further reduce the core density necessary for detachment at a fixed power.

## 4. Effect of RDP on core impurity concentration

Employing the UEDGE code to determine the impurity transport, we started with carbon sputtered off the divertor plates, the private flux wall, and the outer wall. Two operating regimes were considered for detached inner and outer divertors; higher density operation with the lower divertor (discussed by Lasnier, at this Meeting) and lower density operation in the upper, RDP divertor. From the results of the density and power scan, we showed that it was possible to achieve detachment at nearly half the density for a given power in the RDP as opposed to the lower divertor. Therefore we examine core impurities in an upstream density of $3.0 \times 10^{19}$ $m^{-3}$ in the RDP compared to $6.5 \times 10^{19}$ $m^{-3}$ in the open divertor for similar sputtering coefficients.

The main result is that the impurity content is somewhat higher in the RDP than that found for the open divertor simulations, although the two are similar in their relationship to the detachment boundary. This undesired result can be attributed to the lower upstream density used in the RDP simulations, where the particle flux across the separatrix is less than half that of the open divertor (1500 vs. 3700 A, both at 3 MW power). This leads to less parallel flow down the SOL, and hence poorer impurity entrainment. These results emphasize the importance of careful design of experiments if one wants to operate at low upstream density, as is desired for advanced tokamak (AT) operation in DIII-D.

## Acknowledgements

Work was performed for the US Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

## References

[1] S.L. Allen et al., in: Proceedings of the 24th EPS Conference, vol. 21A, Part III, 1997, p.1129.
[2] G. Matthews, J. Nucl. Mater. 220–222 (1995) 104.
[3] G.D. Porter et al., Phys. Plasmas 3 (1996) 1967; T. Rognlien, et al., J. Nucl. Mater. 196–198 (1992) 347.
[4] S.L. Allen et al., J. Nucl. Mater. 220–222 (1995) 336.
[5] C.M. Greenfield et al., Bull. Am. Phys. Soc. 42 (1997) 1980.