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UEDGE Modeling of the Effect of Divertor Modifications on Divertor Performance

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Abstract. The DIII–D upper divertor will be modified in late 1999 by installing a continuous dome in the private flux region with an independent pumping capability for the inner strike point. A "bump" on the inner cylinder also has been considered to enhance impurity and neutral control. Using the UEDGE code, we have examined the effect of this dome and the "bump" on core ionization and core impurity content. For typical parameters, results indicate that the planned divertor modifications enable detachment at higher heating power and the "fueling efficiency" (ratio of core neutral ionization rate to total divertor ion current) decreases, however, the core carbon content increases. The inner "bump" does enhance "fueling efficiency" compared to the private flux dome alone, but it does not reduce the increased core impurity content.

Introduction

This paper compares the physics of the installed Radiative Divertor Program (RDP) divertor in the upper part of the DIII–D tokamak to the effect of the planned modifications to that divertor through the use of UEDGE simulation with experimentally derived plasma parameters [1]. To enhance both impurity and neutral control, the DIII–D upper divertor will be modified in late 1999 by installing a continuous toroidal dome in the private flux region and providing an independent pumping capability for the inner strike point (Fig. 1). The addition of a "bump" on the inner cylinder (to enhance the divertor performance) also has been considered.

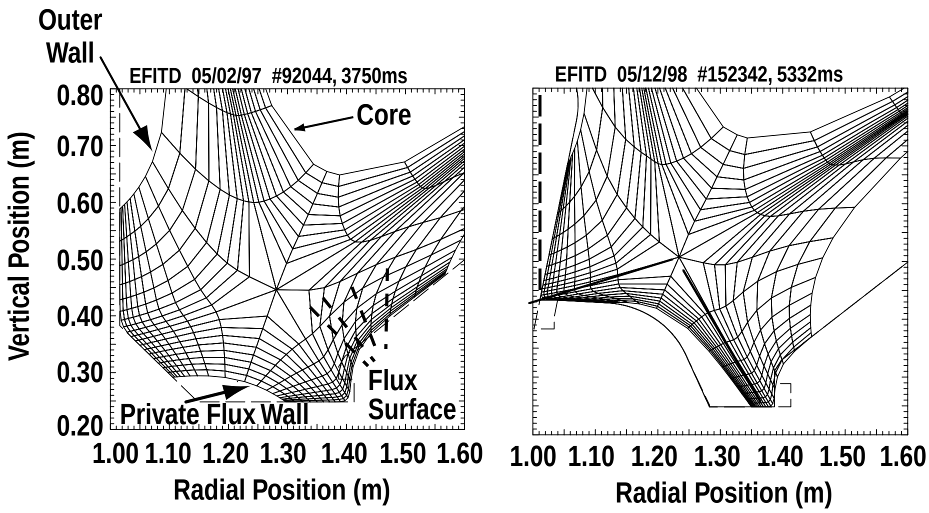

Fig. 1. UEDGE 2–D grid simulation of the upper divertor in DIII–D. (a) The present RDP divertor. (b) Planned private flux dome with "bump."

The RDP is a nearly closed baffle and cryopumping system in the upper divertor of DIII–D [2]. One measure of the effectiveness of the planned modifications is the achievement of a detached plasma with a lower core density than in the present RDP. Plasma detachment, observed on all diverted tokamaks, is a change in the plasma state that results in a decrease in both the ion current and heat load on the divertor plate. Our UEDGE simulations show that the planned modifications will enable detachment at higher heating powers (or lower core densities) and reduce the "fueling efficiency" (ratio of core neutral ionization rate to total divertor ion current) by a factor of 7 for the dome with inner "bump," and a factor of 4 with the dome alone. Thus UEDGE predicts that the planned dome will increase divertor performance in the area of neutral control. However, either with or without the inner "bump," the core carbon concentration increases by a factor of more than 3 compared to the RDP alone.

UEDGE Modeling of the SOL and Divertor in DIII–D

UEDGE is a 2–D, hydrogenic fluid code that simulates the plasma and neutrals in the edge and scrapeoff layers (SOL) in toroidal devices [1]. The code solves the fluid equations for particle, energy, and momentum balance on a 2–D poloidal flux-based grid structure. The electrostatic potential is solved self-consistently, but the effect of drifts are not included. The geometry of the RDP case is fixed as an upper single null. 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. Fixed anomalous perpendicular diffusion coefficients were used in simulations for the lower and upper divertors, namely for the density, D_{perp} = 0.13 m^2/s, and for the electron heat diffusivity, $\chi_e = \chi_i$ = 0.52 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 entrance to the RDP baffle, and for the dome simulation an additional 5% ion removal is specified at the inside entrance of the dome.

Our UEDGE calculation included the effect of the intrinsic carbon impurity introduced by sputtering from the walls of DIII–D. We assumed carbon originated from the private flux and outer wall via chemical sputtering and from divertor plates by a combination of chemical and physical sputtering. The sputtering coefficient was derived from the modified Davis and Haasz sputtering model [3]. These input parameters were then fixed in UEDGE, and the response of the plasma to changes in the SOL heating power was examined.

UEDGE Modeling of RDP and the Private Flux Region Dome in DIII–D

Divertor performance can be measured in two ways that can help us determine the efficacy of the planned modification. A good divertor should minimize the "fueling efficiency," or the fraction of neutrals recycling from the divertor that are ionized in the core. In addition, a good divertor should minimize the average impurity concentration in the core, here measured in the outer midplane of DIII–D. For a set of typical plasma parameters in the RDP, a heating power of 9.0 MW and core density of 3×10^{19} (of special interest to Advanced Tokamak current drive plasmas) the UEDGE simulation shows that the plasma is attached at both the inner and outer plates of this divertor as can be seen in Table 1. However, in the modified divertor (the planned private flux region dome with "bump") both legs of the divertor are strongly detached, with the electron temperature at the plate decreasing by 80%. When the heating power is increased, the inner leg remains detached up to 24 MW, the highest power examined. The outer leg remains detached for powers below 20 MW, as seen in Fig. 2. 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. In addition, with the private flux dome and "bump" in the divertor, there is a decrease of a factor of 7 in the "fueling efficiency." We think that because of the reduced ion temperature (in UEDGE it is the same as neutral temperature) at the plates, the neutrals have a smaller mean-free path and their flux into the core is reduced compared to the RDP case.

Table 1. UEDGE results for three upper divertor geometries: the present RDP; the planned private flux dome with inner “bump;” and private flux dome without the “bump.”

Core Power = 9.0 MW Core Density = $3{\times}10^{19}$ m^{-3}	**A RDP**	**B/A**	**B Dome with “Bump”**	**C/B**	**C Dome No “Bump”**	**C/A**
T_e (inner plate) [eV]	6.36	0.20	1.29	0.96	1.24	0.19
T_e (outer plate) [eV]	11.84	0.18	2.17	1.12	2.43	0.21
Plate current, I_p [A]	$4.57{\times}10^4$	1.40	$6.38{\times}10^4$	0.86	$5.46{\times}10^4$	1.19
Core ionization [A]	577	0.19	108	1.51	163	0.28
Fueling efficiency	1.26%	0.13	0.17%	1.82	0.31%	0.25
Pumping on plates [A]	540	1.39	750	0.90	678	1.26
Pumping on walls [A]	123	0.66	81	3.10	251	2.04
Carbon concentration	1.19%	3.86	4.59%	1.03	4.72%	3.97

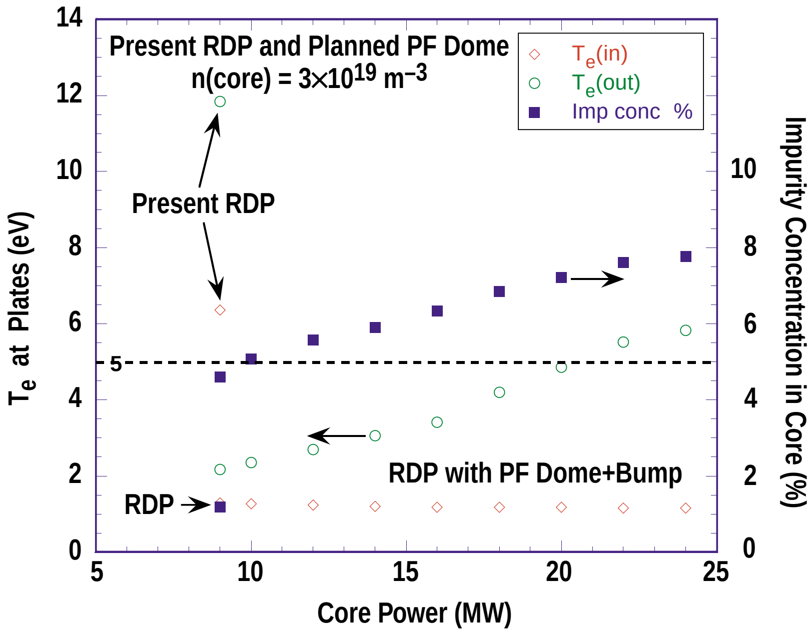

Fig. 2. The electron temperature at the plate and the core impurity concentration of both the present RDP (9 MW heating power) and the planned private flux dome (and “bump”).

However, this favorable result for the planned private flux dome and “bump” is balanced by our UEDGE result indicating an increase in impurity concentration in the core midplane by a factor of more than 3. The higher carbon concentration is due to both an increased carbon source resulting from more recycling in the tighter baffle and also to increased poloidal gradient T_i force. The net force is a balance between this gradient T_i and drag forces, producing a force well near the separatrix. Carbon impurities sputtered from ion and neutral impact on all walls are ionized and result in CV build-up along most of the separatrix due to this force well. The accumulated carbon then enters the core as CV via diffusion, and due to the high core temperature, exits as CVII, as seen in Fig. 3. UEDGE modeling has found that the private flux dome enhances force wells, thus increasing radial flow into the core.

UEDGE Modeling of the Effect of Removing the Inner “Bump”

To help decide whether it is worthwhile to install the inner “bump” in addition to the private flu dome, we simulated the effect when the inner “bump” is removed from the modified divertor. The results for our standard case of Pc = 9 MW and $n_e = 3{\times}10^{19}$ m^{-3} are presented in Table 1, and indicate that when the "bump" is removed from the private flux dome divertor, 1) the electron temperatures at the plates show little change and the plasma remains detached, 2) there is a *50%* increase in core ionization and also current to the plate decreases by 14%, leading to a doubling in the "fueling efficiency" — but this is still a factor of 4 below the present RDP, and 3) the carbon concentration (in the midplane) remains the same within 3%.

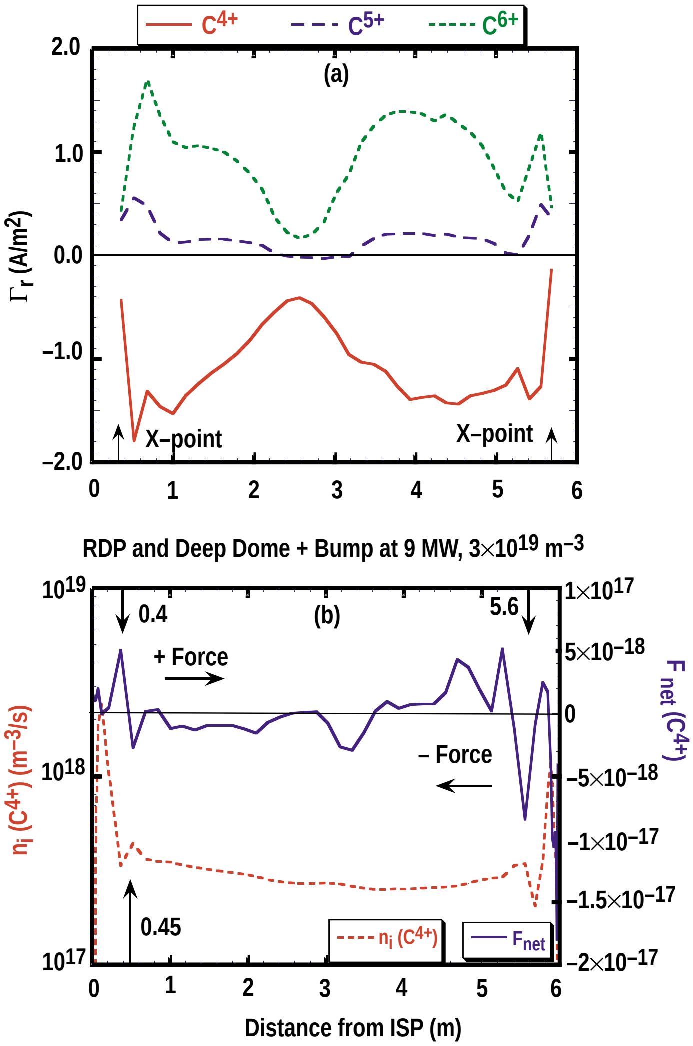

Fig. 3 Uedge simulation of RDP with private flux dome and "bump". a) radial carbon flux of CV, CVI and CVII b) carbon density and net force on CV.

The DIII–D team has reviewed these results and decided that the enhancement in divertor performance due to the "bump" on the inner cylinder is insufficient to compensate for its additional cost and practical problems related to diagnostic interference. The installation of the private flux dome alone is expected to improve divertor control of neutral flow, but the predicted increase in core impurities might pose a problem in future operation.

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