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Indications of an inward pinch in the inner SOL of DIII-D from ^{13}C deposition experiments ☆

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ABSTRACT

^{13}C methane puffing experiments were conducted on DIII-D in both L- and ELMy H-mode conditions. The puffing was toroidally symmetric into the crown of a series of well-characterized lower single-null discharges. The hydrocarbon breakup, carbon transport and deposition were modeled using the OEDGE interpretive code. Three separate hypotheses were tested using OEDGE to try to reproduce the experimental deposition: Radial variation of fast parallel flow, erosion of the puffed ^{13}C deposited in the divertor, and a pinch in the inner scrape off layer (SOL) towards the separatrix. A fast parallel flow was imposed for all hypotheses. The magnitude and the distribution of the ^{13}C deposition resulting from each hypothesis are compared. A fast parallel flow in the SOL toward the inner divertor combined with a pinch/drift of 10–30 m/s in the inner SOL towards the separatrix roughly reproduces the deposition in both the L- and H-mode experiments.

1. Introduction

The carbon–hydrogen co-deposition process does not saturate and could result in an unacceptable buildup of tritium inventory in next-generation fusion devices. There are three distinct aspects to this problem – source, transport and deposition. This paper investigates the transport and deposition of carbon originating from ^{13}C methane puffing experiments on DIII-D under L- and ELMy H-mode plasma conditions. The Onion skin model/Eirene/Divimp edge (OEDGE) interpretative modeling code [1] is used to examine three different carbon transport and deposition hypotheses.

The injection of $^{13}CH_4$ into the edge of tokamaks has been shown on TEXTOR [2], JET [3] and DIII-D [4,5], among others, to provide valuable opportunities for diagnosis of edge transport and carbon behavior. In the first DIII-D experiment, $^{13}CH_4$ was puffed into a set of repeat, lower single-null (LSN), well-controlled, low power, ~1 MW, L-mode discharges. In the second experiment, $^{13}CH_4$ was puffed into neutral beam heated (6.5 MW), detached ELMy H-mode discharges. In both of these experiments, the puff was toroidally symmetric through the upper pumping plenum into the crown of the plasma at a rate which did not significantly perturb the local plasma conditions. Tiles from around the torus were removed after the experiments and the ^{13}C surface content was measured using nuclear reaction analysis (NRA) and proton induced γ-emission (PIGE) [6,7]. The spectroscopic measurements and divertor deposition patterns from both experiments were successfully modeled [8–10]. In both experiments, the region of greatest deposition was in the inner divertor. However, the H-mode experiment also showed substantial deposition in the private flux region (PFR).

Spectroscopic measurements show that the ^{13}C ions formed from the breakup of the $^{13}CH_4$ appear toward the edge of the plasma. Previous modeling showed that if this ^{13}C was transported to the divertor by a uniform parallel flow in the SOL then it would not deposit on the surfaces seen experimentally. Physically, some mechanism is required to move the carbon ions closer to the sep-

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aratrix from the region where they are formed to the region where they are seen to deposit experimentally.

This paper examines and compares the effects of three independent transport and deposition hypotheses.

(a) Effect of radially varying the fast parallel flow, $M_{\|}$.
(b) Effect of erosion of deposited ^{13}C.
(c) Effect of an imposed inward pinch.

Both radial variation of fast parallel flows and erosion have been observed in tokamak experiments. Although there are no direct parallel flow measurements for these experiments, measurements for other discharges have shown both radially constant as well as radially varying flows. Spectroscopic measurements in the L-mode experiment indicated a flow of $M_{\|} = 0.4$.

There are no direct measurements of an inward pinch in the inner SOL. Such a pinch was found necessary by Kirnev et al. [11] in EDGE2D code analysis in order to replicate the measured JET parallel flow pattern. Work by Stacey [12,13], examining the physics associated with pedestal formation just inside the confined plasma, calculates a substantial pinch arising from the conservation of particles, momentum and energy in the pedestal region. This pinch reaches a maximum at the separatrix. Although the analysis does not extend into the SOL, it is possible that conditions outside the separatrix could also lead to a similar inward pinch. Another possible explanation for such a pinch could result from intermittent plasma transport on the high field side (HFS). Plasma fluctuations have been observed on both the high and low field sides of several tokamaks (ASDEX [14], CMOD [15]). These fluctuations typically lead to intermittent outward transport on the low field side of the tokamak [16] but could possibly lead to transport toward the separatrix on the HFS side of the device. On the other hand, HFS intermittent transport on the T-10 tokamak has been measured and would appear to move away from the separatrix towards the inner wall [17].

2. Modeling and results

The first step in the OEDGE analysis was to use all available experimental data and "onion-skin" modeling (OSM) to infer a solution for the background plasma by empirical reconstruction. Empirical plasma reconstruction utilizes experimental data and 1D onion skin models along each flux tube of the modeling grid to generate background plasma solutions which match as much of the experimental data as possible. These plasma solutions are then used as the basis for calculating the transport and deposition of the ^{13}C in the rest of the study. The details of the plasma solutions for the L- and H-mode experiments can be found in previous publications [8,9].

The code imposed a parallel flow toward the inner divertor of specified Mach number, $M_{\|}$. $M_{\|} \equiv v_{\|}/[(T_e + T_i)/m_D]^{1/2}$, $T_i = T_e$ assumed. All of the hypotheses included in the present analysis used a base flow of $M_{\|} = 0.4$. In the pinch and erosion hypotheses, this flow was imposed constant across the SOL while in the radial flow variation cases presented here $M_{\|} = 0.4$ was the maximum value imposed. A value of $D_{\perp} = 0.3\ m^2/s$ for the impurities was also assumed.

The radially varying results reported in this paper utilized six base $M_{\|}$ profiles across the SOL. These six cases included four step function profiles with $M_{\|} = 0.4$ or $M_{\|} = 0.0$ over different regions of the SOL and two linear ramp cases with $M_{\|}$ changing from $M_{\|} = 0.4$ at one edge of the SOL to $M_{\|} = 0.1$ at the opposite edge. These cases were chosen as representative of a larger set of radially varying and constant $M_{\|}$ cases where a wide range of $M_{\|}$ values and profiles were used. $M_{\|}$ in the L-mode experiment extended to near the inner target [8] while in the H-mode experiment the $M_{\|}$ flow stopped in the X-point region of the inner divertor [9].

The pinch/drift term was imposed only in the SOL above the X-point. Simulations were run using both a classical inward (minor radius) pinch and an outward (major radius) drift. Due to the geometry of DIII-D, the difference between these two different transport mechanisms in the inner SOL can not be distinguished experimentally. Simulations using either transport mechanism give similar results. Fig. 1 shows an overview of the flows in the divertor region.

The erosion simulations utilized a constant erosion coefficient across all divertor surfaces. When an erosion event was found to occur, the erosion was simulated by the release of 0.5 eV carbon neutrals. Hydrocarbon evolution code for eroded particles will be added for future work.

The $^{13}CH_4$ gas is introduced in the modeling as neutral molecules through the upper pumping duct. Each $^{13}CH_4$ molecule and resulting ^{13}C particle (atom or ion) is followed using OEDGE through a series of molecular breakup processes, atomic processes, and surface interaction processes until the ^{13}C leaves the simulation by depositing on a surface. The resulting deposition is compared to the experimental values.

Hydrocarbon sticking coefficients from [18] were used in the simulations. Carbon neutrals and ions were assumed to stick when striking a surface except in the erosion simulations where specific probabilities were assigned. Code results are calibrated to the absolute amount of $^{13}CH_4$ puffed and are thus directly comparable to the experimental results for both distribution and magnitude.

The first hypothesis examined is the radial variation of the fast parallel flow. A wide range of radial profiles were examined; the ones best matching the experimental result are shown in the figures. Results for constant flow cases of $M_{\|} = 0$ and $M_{\|} = 0.4$ with no radial variation are also included for reference.

The L-mode deposition is most closely reproduced by a radial variation of the flow that increases from $M_{\|} = 0.1$ at the edge of the modeling grid to $M_{\|} = 0.4$ at the separatrix (RVA – see Fig. 2). However, the deposition peak is smaller than is seen experimentally and occurs inboard of the experimental peak. For the H-mode experiment, a region without flow at the edge of the plasma (about 1/3 of the SOL) with the remainder at a constant flow of

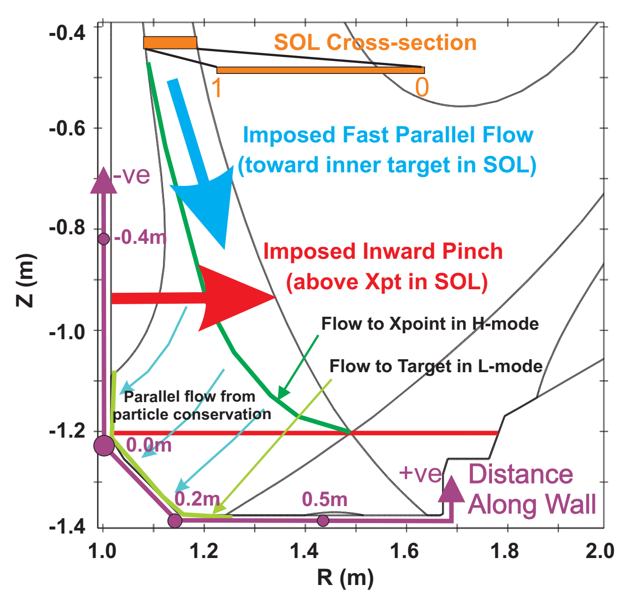

Fig. 1. Schematic of the divertor showing the imposed flows and the axis for the deposition figures.

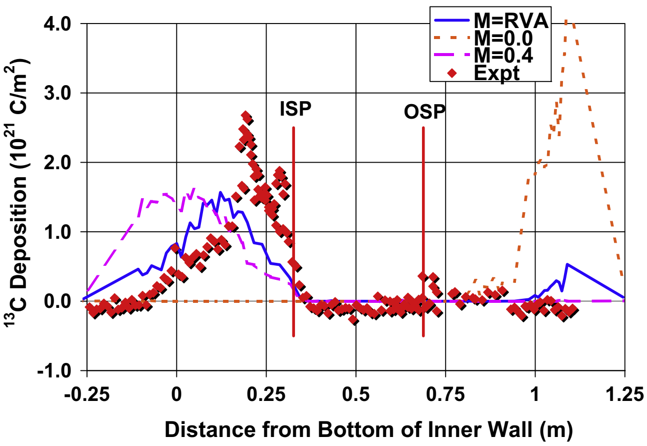

Fig. 2. L-mode deposition resulting from radially varying $M_{\parallel}$ flows.

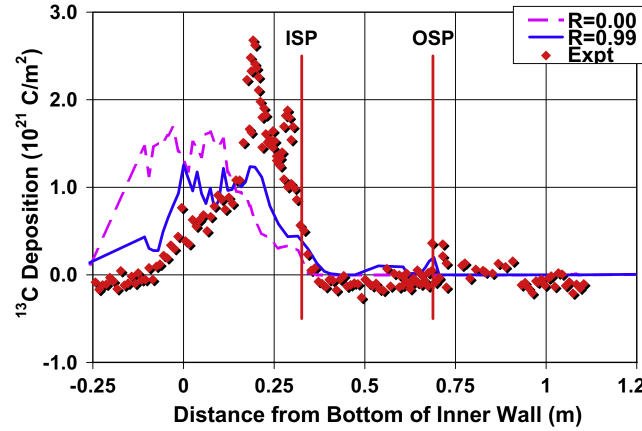

Fig. 4. Effect of erosion on the L-mode deposition.

$M_{\parallel} = 0.4$ gives the closest match to the experimental deposition (RVC – see Fig. 3). However, the absolute magnitude of the deposition is again below the measured values. Reduced flow at the edge of the grid causes increased carbon deposition on the inner wall due to diffusion.

The next hypothesis examined is the effect of erosion. Erosion of ^{13}C on divertor surfaces was simulated by specifying a constant erosion probability across the divertor surface for every carbon particle (atom or ion). Carbon particles that did not stick were released as neutral carbon from the point of impact with 0.5 eV of energy and a cosine distribution. Erosion probabilities of 0.0, 0.5, 0.8, 0.9, 0.95 and 0.99 were used in the simulations. A constant flow of $M_{\parallel} = 0.4$ was used in these cases as described previously.

In the L-mode modeling, erosion shifted the deposition profile so that a peak begins forming close to the location seen experimentally (see Fig. 4). However, in all cases there is insufficient retention of carbon to match the amount deposited. High erosion rates result in carbon escaping the divertor and depositing on the center column or transiting across the PFR to the outer strike point. The H-mode result is similar (see Fig. 5). Erosion rates of 0.8–0.95 appear to result in the formation of a peak close to the inner strike point. However, all of the H-mode erosion scenarios fail to reproduce the deposition on the private flux zone wall.

The third hypothesis examined is the effect of a pinch/drift towards the separatrix in the inner SOL. The pinch is imposed in the major radius direction above the X-point as shown in Fig. 1 in conjunction with the fast parallel flow mentioned previously.

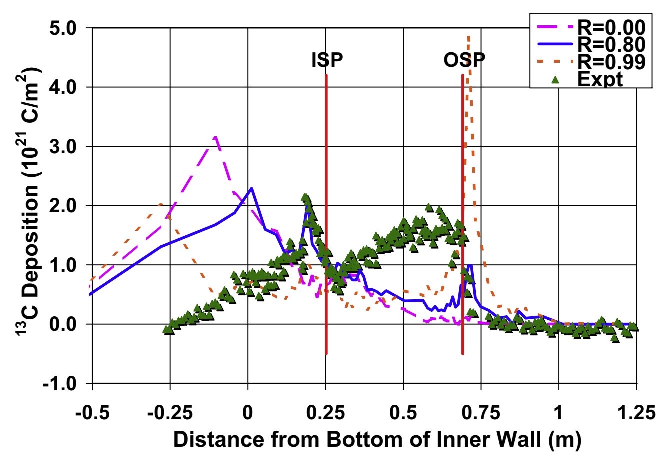

Fig. 5. Effect of erosion on the H-mode deposition.

The L-mode deposition can be roughly reproduced in both pattern and magnitude by imposing a pinch between 20 and 30 m/s (see Fig. 6). In the H-mode experiment a pinch of 10 m/s roughly reproduces both the shape and magnitude of the deposition (see Fig. 7). In both cases the effect of the pinch is to move the carbon deposition closer to the separatrix while reducing the amount of carbon lost to the inner wall through diffusion.

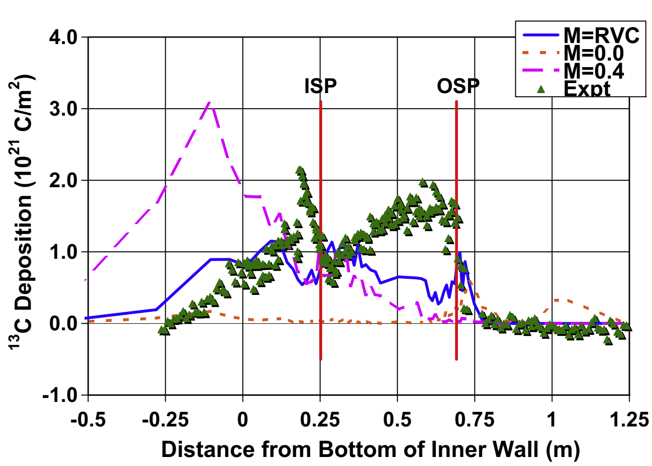

Fig. 3. H-mode deposition resulting from radially varying $M_{\parallel}$ flows.

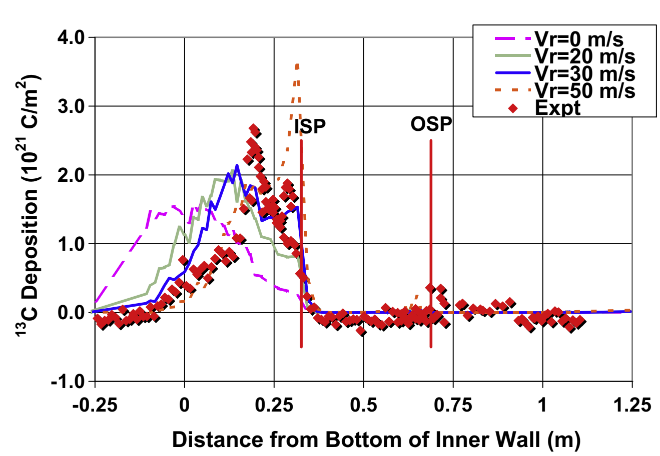

Fig. 6. L-mode deposition dependence on an inward pinch.

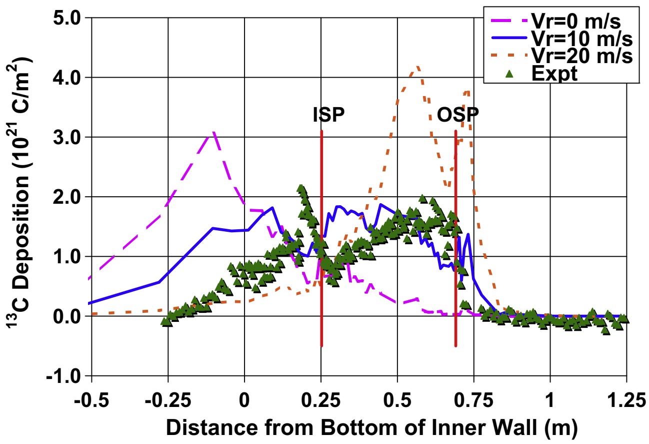

Fig. 7. H-mode deposition dependence on an inward pinch.

3. Discussion

The results presented in the previous section show that, of the three hypotheses examined, only a pinch, in combination with a fast parallel flow of $M_{\parallel} = 0.4$, is able to roughly reproduce both the distribution and magnitude of the experimental deposition profiles. Deposition results for the pinch hypothesis are consistent with the experimental deposition for values of a pinch between 10 and 30 m/s. However, there are several additional considerations.

Both radially varying flow and erosion can replicate certain features of the observed deposition. Radially varying flow scenarios in both L- and H-mode can replicate most of the distribution features of the deposition patterns. However, in both cases insufficient carbon reaches the divertor to match the experimental deposition. Similarly, erosion simulations with very high erosion probabilities show an accumulation of carbon near the location of the inner target deposition peak seen experimentally in both L- and H-mode. However, large erosion rates also lead to redistribution of deposited carbon onto the inner wall and to the outer target. In addition, the erosion hypothesis appears unable to account for the deposition observed in the PFR in the H-mode experiment. This result though needs to be examined more carefully using a hydrocarbon model for the eroded carbon. It is possible that hydrocarbon molecules would find the cold and dense PFR more difficult to penetrate than the low energy carbon neutrals that were used in these simulations.

The effect of global changes in $D_{\perp}$ on the deposition was also examined. Values of $D_{\perp}$ from 0.01 to 10 m^2/s were used. The larger the value of $D_{\perp}$, the broader the deposition profile. However, since the $^{13}C^{+}$ is formed relatively close to the edge of the plasma, any increase in $D_{\perp}$ allowing for a broader target deposition also depleted the amount of carbon reaching the divertor through deposition on the inner wall.

So far, the only hypothesis in which sufficient carbon reaches the divertor to roughly match the experimental profiles, has been found to be one requiring the imposition of a pinch and a fast parallel flow toward the inner divertor. Although all the hypotheses tested are capable of replicating some aspects of the deposition pattern, only the pinch hypothesis has been found able to replicate both the rough distribution and magnitude of the observed deposition.

4. Conclusions

This paper has examined the effect of three different transport and deposition hypotheses on the expected distribution and magnitude of carbon deposited in the divertor in two separate experiments on DIII-D. Analysis of these effects indicates that neither the radial variation of the parallel flow nor erosion, by themselves, is sufficient to reproduce the experimental deposition. These effects can reproduce important features of the deposition distribution but in both cases the carbon deposited in the divertor is less than is seen experimentally.

A more complete analysis of transport and erosion hypotheses in the $^{13}CH_4$ puffing experiments has been performed. Although it is probable that radial flow variation and erosion processes are occurring in the experiment, the simulation results indicate that in all cases a pinch in the inner SOL of DIII-D during these experiments may be needed to reproduce the magnitude of the measured deposition.

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