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OEDGE modeling of ^{13}C deposition in the inner divertor of DIII-D

J.D. Elder[a], P.C. Stangeby[a,b,c], D.G. Whyte[d], S.L. Allen[c], A. McLean[ab], J.A. Boedo[e], B.D. Bray[b], N.H. Brooks[b], M.E. Fenstermacher[c], M. Groth[c], C.J. Lasnier[c], S. Lisgo[a], D.L. Rudakov[e], W.R. Wampler[f], J.G. Watkins[f], and W.P. West[b]

[a]*University of Toronto Institute for Aerospace Studies, University of Toronto, Canada*

[b]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*

[c]*Lawrence Livermore National Laboratory, Livermore, California, USA*

[d]*University of Wisconsin – Madison, Madison, Wisconsin, USA*

[e]*Univeristy of California – San Diego, La Jolla, California, USA*

[f]*Sandia National Laboratory, Albuquerque, New Mexico, USA*

Abstract

Use of carbon in tokamaks leads to a major tritium retention issue due to co-deposition. To investigate this process a low power (no beams) L-mode experiment was performed on DIII-D in which $^{13}CH_4$ was puffed into the main vessel through the toroidally-symmetric pumping plenum at the top of lower single-null discharges. Subsequently, the ^{13}C content of tiles taken from the vessel wall was measured. The interpretive OEDGE code was used to model the results. It was found that the ^{13}C deposition pattern is controlled by: (a) source strength of $^{13}C^+$, (b) radial location of the $^{13}C^+$ source, (c) $D_\perp$, (d) $M_\parallel$, the scrape-off layer parallel Mach number. Best agreement was found for (a) ~50% conversion efficiency $^{13}CH_4 \rightarrow {}^{13}C^+$, (b) $^{13}C^+$ source ~3.5 cm outboard of separatrix near $^{13}CH_4$ injection location, (c) $D_\perp \sim 0.3\ m^2s^{-1}$, (d) $M_\parallel \sim 0.4$ toward inside.

JNM keywords: T0100, C0100 I0100, P0600, D0500

PSI-16 keywords: Carbon Impurities, DIII-D, Edge Modeling, Impurity Transport, OEDGE

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[*]Corresponding author address: D. Elder, University of Toronto Institute for Aerospace Studies, 4925 Dufferin St., Downsview ON Canada M3H 5T6

[*]Corresponding author e-mail: david@starfire.utias.utoronto.ca

Presenting author address: See above

Presenting author e-mail: See above

I. Introduction

The carbon-hydrogen co-deposition process does not saturate and could result in an unacceptable build up of tritium inventory. There are three principal questions: (1) What is the source of the carbon? (2) What transport mechanism carries the carbon in the scrape off layer? (3) What determines the final resting place of the carbon? This paper is an interpretive modeling investigation related to the 2nd and 3rd questions.

A well-controlled low power, ~1 MW, simple as possible plasma (SAPP) L-mode experiment was run on DIII-D in which $^{13}CH_4$ was puffed through the upper pumping plenum of lower single-null (LSN) discharges [1]. This puff was toroidally symmetric and at a rate which did not significantly perturb the local plasma conditions. The puff rate was limited so that the increase in the measured carbon density in the core was modest, ~35%. The ^{13}C was puffed for 22 consecutive identical discharges for a period of 3 s during each discharge under steady-state plasma conditions. After the experiment, 29 tiles were removed and the ^{13}C content was measured using nuclear reaction analysis [2]. For these conditions, detectable ^{13}C deposition was only found for tiles in the inner divertor region.

The Osm Eirene Divimp edge (OEDGE) code [3] was used in this study to model the transport and deposition of the ^{13}C. The objective was to identify and quantify the controlling factors governing the ^{13}C deposition pattern. It is found that the ^{13}C deposition pattern and core ^{13}C-content are essentially controlled by four quantities: (a) the source strength of $^{13}C^+$, (b) the radial location of the $^{13}C^+$ source, (c) $D_{\perp}$, (d) $M_{\parallel}$, the parallel Mach number. Large values of $M_{\parallel}$ toward the inside, in the scrape-off layer (SOL) at the top (LSN divertor), have been measured in a number of tokamaks, but attempts to explain/model this flow have been unsuccessful to date. Separately reported OEDGE analysis [4] is used to model (a) and (b). Here all four control parameters are treated as unknowns and the range of their permitted

values is “backed out” of the interpretive code analysis by comparison with the experimental measurements.

II. Results

The first step in the OEDGE analysis was to use all available experimental data and the “onion-skin” modeling (OSM) in OEDGE to infer a solution for the background plasma by empirical reconstruction. (There is insufficient space in the present paper to adequately describe this modeling method, but a very similar reconstruction exercise, also for a detached DIII-D divertor case, is reported in these proceedings [5].) This plasma solution (identified as OSM in the figures) is then used as the basis for calculating the transport and deposition of the ^{13}C in the rest of the study. The experimental data used here included calibrated spectroscopic measurements of $D_{\square}$, $D_{\square}$ and $D_{\square}$ for both the inner and outer targets, target Langmuir probe measurements of I_{sat}^{+}, and upstream measurements of the plasma profiles. The plasma solution obtained by this empirical modeling used the Langmuir probe I_{sat}^{+} as input (Fig. 1). The solution matched the hydrogenic spectroscopy (EIRENE-calculated profiles) (Fig. 2) at the inner and outer targets as well as the upstream plasma measurements (Fig. 3). The inner target was found to be detached with a near target plasma temperature of 0.8 $\pm$ ~0.2 eV. The $D_{\square}$, $D_{\square}$, $D_{\square}$ are extremely sensitive “T_e thermometers” in these cold, dense conditions, providing most valuable, and precise, input to the empirical reconstruction of the inner plasma, see Ref. [5]. Superimposed by the code on the plasma solution was a parallel plasma flow of specified Mach number, $M_{||}$, extending from near the outer target to near the inner one. $M_{||} \equiv v_{||} \Big/ \left[(T_e + T_i)/m_D \right]^{1/2}$, $T_i = T_e$ assumed.

The ^{13}C deposition measurements found no significant ^{13}C deposition (above background) anywhere other than the inner target region. The experimental deposition is shown with the model results below.

A series of simulations were run where the parallel flow was specified, radially constant, varying from $M_{\parallel} = 0.05$ up to $M_{\parallel} = 2$, all with $D_{\perp} = 0.3 m^2/s$. ^{13}C was launched in DIVIMP as $^{13}C^+$ at the top of the torus, 3.5 cm outboard of the separatrix. The calculated ^{13}C deposition patterns are shown in Fig. 4. The experimental profile is best matched by $M_{\parallel}$ of ~0.4. If the flow in the SOL is too slow the deposition spreads out on the inner target and significant deposition is seen on the inner wall — contrary to observation. If the SOL flow is too fast then the deposition profile on the inner target becomes too narrow. This result indicates that the SOL flow lies in the range $M_{\parallel}$ = ~0.3–0.6 directed toward the inside. Assumption of flow, at any speed, toward the outside completely fails to match the measured deposition pattern. From the comparisons in Figs. 4 through 6, a conversion efficiency of ~50% was inferred (this value was used for the code results). Raising or lowering the efficiency simply changes the vertical scale on these figures for the code results. In the next study the parallel flow was fixed at $M_{\parallel} = 0.4$ with same C^+-source location, while the value $D_{\perp}$ was varied. Results in Fig.□. In this case, smaller values of $D_{\perp}$ cause the target deposition profile to become more peaked while the larger $D_{\perp}$ values spread the deposition out across the target. The larger values of $D_{\perp}$ give more deposition on the inner wall. The transport is dominated by the parallel flow. It is concluded that $D_{\perp}$ ~ 0.3–0.5. In the next study, ^{13}C ions were started at different radial locations upstream. $M_{\parallel} = 0.4$, $D_{\perp} = 0.3\ m^2/s$. The launch locations varied from inside the separatrix to the middle of the SOL. Results are shown in Fig. 6. The launch location shown is the perpendicular distance from the separatrix. Starting too far out in the SOL results in significant inner wall deposition and a target deposition peak located too far from the inner strike point. On the other hand, a source too close to the separatrix moves the deposition peak inward toward the strike point. It is concluded that the $^{13}C^+$ source is located at 3-6 cm outboard of the separatrix. In addition to the deposition pattern, the total carbon density at separatrix places another constraint on the four control parameters. Table I shows

the separatrix C-density for each of these simulations. The experimentally measured increment to the separatrix C-density as a result of the puff is 2.0×10^{16} C/m^3, from charge exchange recombination spectroscopy (CER) measurements. $M_{\parallel} \sim 0.4$ to 0.6, $D_{\perp} \sim 0.3$m^2/s, and ions starting at the 3.5 cm flux surface are consistent with the total amount of carbon entering the core plasma as well as the deposition pattern. For the majority of cases there is little or no deposition anywhere but in the inner divertor region. The only exception was for $M_{\parallel} = -0.05$ where ~25% of the particles deposited on the inner wall and ~8% on the outer target.

III. Discussion

The foregoing analysis constitutes a first, simple treatment. It nevertheless appears adequate to identify approximate values for the four main control parameters. The inferred $M_{\parallel} \approx 0.4$ and radial location of the C^+-source agrees with analysis of the CII and CIII intensity distributions near the gas inlet measured by tangential viewing cameras [4]. A number of refinements will be included in future work. A potentially important effect, which has not been included in the present analysis, is the erosion and re-deposition of the ^{13}C particles which strike the inner target — i.e. the redistribution of the ^{13}C resulting from the ongoing plasma exposure. Preliminary modeling of the erosion and re-deposition patterns at the inner target indicates that the entire target is a net deposition region, which tends to justify the neglect of erosion and re-deposition for the *present* case. This simplifying aspect of the present experiment cannot be expected generally. On JET, the ^{13}C that initially arrived at the inner target did not stop there but continued on to deposit on adjacent surfaces that were out of plasma contact [6]. The rather low input power of the present L-mode SAPP experiment has resulted in this very valuable simplification. In future studies, erosion and re-deposition are likely to play a more important — and possibly totally dominating — role. Including this

effect will constitute a substantially increased challenge to the modeling, since the details of the inner divertor plasma will play a much more important role than in the present case. It is therefore very valuable to have the most basic case successfully analysed. We can now proceed more confidently to the more challenging cases knowing that we understand — or at least can characterize quantitatively — the problem up to the point of the initial deposition on the inner target.

IV. Conclusions

This study identified and quantified four control variables governing the ^{13}C deposition and core contamination behaviour: (a) ~50% conversion efficiency of $^{13}CH_4$ to $^{13}C^+$, (b) $^{13}C^+$ source ~3 to 6 cm outboard of the separatrix near the $^{13}CH_4$ injection location, (c) $D_{\perp}$ ~ $0.3\,m^2s^{-1}$, (d) $M_{\parallel}$ ~ 0.4 toward inside. Modest variations of each of these quantities are also consistent with experiment. There is no evidence, for the plasma conditions involved in the present study, of substantial erosion and re-deposition of the ^{13}C. It thus constitutes the simplest possible case and provides a valuable basis on which to proceed to the general case where redistribution of the initial deposition pattern occurs by ongoing plasma impact.

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Table I. Density of carbon just inside the core plasma for a range of simulation conditions.

Case $M_{\parallel}$	Core Edge Density (C/m^3)	Case $D_{\perp}$	Core Edge Density (C/m^3)
M=2.0	1.40E+15	$D_{\perp}$=1.0	2.59E+16
M=1.5	2.94E+15	$D_{\perp}$=0.5	2.58E+16
M=1.0	6.25E+15	$D_{\perp}$=0.3	2.61E+16
M=0.9	8.74E+15	$D_{\perp}$=0.1	1.40E+16
M=0.8	9.74E+15	$D_{\perp}$=0.05	4.50E+15
M=0.7	1.19E+16		
M=0.6	1.50E+16	D_{sep} (cm)	
M=0.5	1.93E+16	11.35cm	9.36E+14
M=0.4	2.61E+16	9.22cm	2.92E+15
M=0.3	3.66E+16	7.23cm	6.68E+15
M=0.2	5.81E+16	5.35cm	1.33E+16
M-0.1	1.14E+17	3.56cm	2.61E+16
M=0.05	2.11E+17	1.87cm	4.40E+16
		0.26cm	7.88E+16
		-0.28cm	9.65E+16

Figure Captions

Fig. 1. Comparison of Langmuir Probe I_{sat} and OSM Input I_{sat}. The I_{sat} is one of the key inputs to the OSM. Ψ_n is the normalized magnetic coordinate.

Fig. 2. (a,b,c) Comparison of the experimental and modeled D_α, D_β and D_γ spectroscopy at inner target. All figures are scaled in units of photons/m^2/s/sr. The modeled hydrogen spectroscopy is produced by EIRENE running with the OSM plasma solution as input. This identified the value of T_e at the inner target as ~0.8$\pm$0.2 eV.

Fig. 3. Comparison of upstream n_e and T_e for Thomson (TS), reciprocating probe (RCP) and the OSM solution. The TS and RCP profiles did not line up exactly, perhaps due to uncertainties in the identifying the separatrix locations, and were slightly shifted (Thomson outward by 0.01 Ψ_n and RCP inward by 0.03 Ψ_n) to match the OSM result. The OSM profiles are essentially based on the target plasma conditions, where the location of the separatrix may be easier to identify, e.g. from the peak in the I_{sat} profile, Fig. 1.

Fig. 4. Deposition as a function of $M_{\parallel}$ — the parallel flow Mach number.

Fig. 5. Deposition as a function of D_α.

Fig. 6. Deposition as a function of initial $^{13}C^+$ radial position plotted as the distance to the launch position from the separatrix.

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