DIVIMP modeling of the toroidally-symmetrical injection of $^{13}CH_4$ into the upper SOL of DIII-D

A.G. McLean[a,b], J.D. Elder[a], P.C. Stangeby[a,b,c], S. Allen[c], N. Brooks[b], M. Fenstermacher[c], M. Groth[c], S. Lisgo[a], A. Nagy[b,d], W. Wampler[e], J. Watkins[e], W.P. West[b], D.G. Whyte[f]

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

[b] *General Atomics*

[c] *Lawrence Livermore National Laboratory*

[d] *Princeton Plasma Physics Laboratory*

[e] *Sandia National Laboratory*

[f] *University of Wisconsin – Madison*

Abstract

As part of a study to elucidate carbon-tritium co-deposition, an experiment was carried out on DIII-D involving a toroidally symmetric injection of $^{13}CH_4$ at the top of the vessel (LSN divertor). The focus here is on interpretation of the region near the gas injection point using a Monte Carlo code, DIVIMP-HC, which models molecular breakup. The interpretive analysis indicates a parallel flow in the SOL of $M_{||} \sim 0.4$ directed toward the inner divertor and $D_{\perp} \sim 0.3$ m^2/s. For such a wall injection location most of the CH_4 gets ionized, becomes C^+, and is efficiently transported along the SOL as C-ions to deposit in the inner divertor. The CH_4 is ionized deeply in the SOL and so the 'contamination efficiency' of the confined plasma is not high: the confinement time is only ~ 5 ms, about 4X lower than if the CH_4 were ionized at the separatrix.

Introduction

Carbon is commonly used for first wall and target coverage, and since it is susceptible to chemical sputtering, studies have been carried out on most tokamaks using injection of known flow rates of methane to evaluate the magnitude and characteristic radiative emissions associated with chemical sputtering. Ref. [1] provides an extensive set of references for methane injection experiments including studies on core carbon transport, plume characterization, erosion and re-deposition, molecular break-up studies, and evaluation of carbon penetration through the SOL to the core.

On DIII-D an experiment has been carried out [2] involving the injection of $^{13}CH_4$ at the top of the torus, similar to one carried out on JET [3], aimed at elucidating certain aspects of the carbon-tritium co-deposition process, which has serious implications for tritium retention in ITER. This injection is unusual in being toroidally-symmetrical – CH_4 injection was through the upper outer pumping plenum (Fig. 1) – thus justifying the standard, but often not satisfied, code assumption of symmetry. Based on the earlier $^{13}CH_4$ puffing experiments on JET, it is believed that a large scale convective pattern in the SOL, which transports wall-released C along the main SOL, over the top of the vessel, and down into the inner divertor, led to the observation of strong retention of tritium in the inner divertor of JET and very little in the outer divertor. One of the objectives of the present experiment was to obtain direct visual confirmation of this convection pattern using toroidal cameras and vertical filterscopes viewing the injection region. A second objective was to establish the efficiency with which wall-released methane is converted to C-ions (i.e. not being lost back to local solid surfaces as neutral and charged molecular fragments). One of the main contributors to C subsequently appearing in H/D/T co-deposits may be chemical sputtering of the walls. The efficiency of conversion to C-ions is likely to be much higher for wall sources than for release from divertor targets where prompt local re-deposition can be strong due to the fast, strongly collisional plasma flow to the targets. A third objective was to measure the efficiency of core contamination of such a toroidally symmetric wall source.

A methane-break-up module has been added to the OEDGE [4] (DIVIMP) code in order to interpretively model the results of the injection of $^{13}CH_4$ into DIII-D [5].

Experiment and Modeling

The experiment was carried out over 2 days, with ordinary $^{12}CH_4$ being used on the first –'plasma characterization' – day, and with many repeat shots to maximize edge diagnosis. The rate of injection, 4.4 tl/s, was established by adjustment to achieve an approximate 35% increase of core carbon density, as measured by CER (CVI), over the no-injection base. This condition was chosen to give a large enough injection rate to get measurable effects without disturbing the plasma. The fact that the injection was not localized – but was distributed in a toroidally symmetric way – greatly helped to further reduce the risk of significantly changing the plasma at the location where the gas entered – which is the most critical location. Injection lasted for 3.0 s in each discharge, beginning after stable L-mode conditions were achieved. The $^{13}CH_4$ puffing was repeated over a series of 22 consecutive identical discharges on the 2nd day. More details of the experiment are provided in [2]. The ^{13}C deposits turned out to be almost entirely on the inner divertor target [6]. The deposition itself has been modeled using the OEDGE interpretive code [7]. The focus of the present paper is on the region near the injection location, also interpreted using the OEDGE code, but with the addition of a module DIVIMP-HC that follows the molecular break-up kinetics (presently using the simple data base of Ehrhardt and Langer [8], preliminary to upgrade to the more exhaustive data base of Janev and Reiter [9]).

Data from the toroidally viewing camera were processed to give 2D reconstructions of the CII (at 514 nm), i.e. C^+, and CIII (at 465 nm), i.e. C^{++}, 'clouds', Fig. 2. The reconstruction was made possible by the fact that the injection was toroidally symmetric. It is evident that the CIII is shifted toward the inner divertor, relative to the CII, indicative of strong parallel flow along the SOL toward the inside. It is also possible that the transport is actually poloidal, but the hypothesis here is that the transport is parallel – or *effectively* parallel.

Such fast parallel flows in the main SOL have been reported in other tokamaks, measured for example with Mach probes [10, 11, 12]. The driving mechanism has not as yet been identified. Therefore in the OEDGE modeling used here a value of the parallel flow speed is simply specified as part of the 'plasma background', which is then used as input to the Monte Carlo DIVIMP-HC code. The radial profiles of n_e and T_e are taken from a combination of measurements from Thomson scattering (TS) and a reciprocating probe (RCP), Fig. 3, plus an OSM solution generated by Elder [7]; the TS and RCP profiles did not precisely match – perhaps due to EFIT uncertainties – however, small shifts resulted in good agreement for all 3 profiles, for both n_e and T_e. The 'plasma background' used here is very simple: radial profiles of n_e and T_e (= T_i, assumed) that are taken to be constant along the field lines, and a parallel flow speed that is also invariant along the field lines. The parallel flow was specified via Mach Number, $M_{||}$: the value of $M_{||}$ at the separatrix, $M_{||sep}$, was specified, and was assumed to vary radially, linearly decreasing to $M_{||sep}/4$ at the outermost 'ring' of the computational grid, Fig. 1. The other main adjustable was the cross-field diffusion coefficient, $D_\perp$, which was taken to be spatially constant. A large number of OEDGE code runs were made, varying $M_{||sep}$ and $D_\perp$, searching for the solution which best met the following constraints:

1. Matching the CII and CIII 'clouds' measured by the toroidally-viewing cameras, Fig. 2.
2. Matching the poloidal distribution of CIII (at 465 nm) light measured by the absolutely calibrated Filterscope, which viewed the gas injection region from below, Fig. 1.
3. Matching the C^{6+} density in the confined plasma, as measured by CER, which indicated a total C-ion density just inside the separatrix of $2\text{x}10^{16}$ m^{-3} $\pm$ 50%.

It is possible to get a qualitative impression of the degree of match between code and the camera 2D CII, CIII 'clouds' just by looking at the plots. Fig. 4 shows a particular code result ($M_{||sep}$ = 0.4 and $D_\perp$ = 0.3 m^2/s) which appears to be reasonably close to the camera pictures, Fig. 2. However, in order to make quantitative comparisons, the camera data were processed to produce poloidal profiles (coordinate center at machine center, and poloidal angle measured CCW from vertical), by integrating along the radial lines extending from the machine center. Fig. 5 shows the camera results for CII and CIII, together with results for $M_{||sep}$ ranging from 0 to 1, all using $D_\perp$ = 0.3 m^2/s. As can be seen, the best match is for $M_{||sep}$ ~ 0.4. Similar comparisons were used to establish that $D_\perp$

~ 0.3 m^2/s gave the best match and similar comparisons assuming radially constant $M_{||}$ and also radially constant $v_{||}$, indicated that the radially varying $M_{||}$ gave the best match.

The same sort of quantitative comparison can be made with the Filterscope CIII poloidal distribution and in Fig. 6 the experimental results are compared with the code results, again for $M_{||sep}$ ranging from 0 to 1, all using $D_{\perp} = 0.3\ m^2/s$. It is seen that, again, $M_{||sep} \sim 0.4$ gives the best match. The comparison in Fig. 6 is based on normalizing the experimental, as well as each code result, to have unity peaks. Fig. 7 shows the comparison of the absolutely calibrated filterscope CIII profile and the code result for $M_{||sep} = 0.4$ and $D_{\perp} = 0.3\ m^2/s$ also gives the best agreement as to the magnitude of the CIII emission. Fig. 8 shows the Filterscope CIII poloidal profiles for 3 different gas rates, the smallest rate being that used for the actual $^{13}CH_4$ shots, which was also the rate used for set-up shot 116208, between 2000 and 2250 ms. For the latter shot, 2 higher flow rates were also used, with the highest rate being 4X the ‘base’ rate. As can be seen, the profiles are essentially the same for all the flow rates used, indicating that the gas puff is not itself causing the SOL plasma flow, but is providing a valid way to measure the pre-existing flow, i.e. $M_{||}$.

The comparison of the measured C-ion density just inside the separatrix, $2x10^{16}\ m^{-3} \pm 50\%$, and the code values are given in Fig 9, and indicates a value of $M_{||sep} \sim 0.5$. Taking into account the radial profile of the C-ions in the main plasma, from CER, the particle confinement time is found to be $\tau_c \sim 5.5$ msec (where $\tau_c \equiv$ (total core content)/(methane puff rate)). This value is fairly close to the values reported by West [13], of ~ 10 ms, also for CH_4 puffing into DIII-D, although using localized wall puffing. The closely related OEDGE modeling of Elder [7] showed that τ_c would be ~4X higher if the CH_4 were ionized at the separatrix, rather than at the actual location - ~ 3 cm radially outside the separatrix. Thus the main plasma is fairly well shielded from such a wall source of methane – and thus, by implication, for wall chemical sputtered sources.

DIVIMP-HC results showed that only ~40% of the puffed CH_4 was locally deposited (as neutral fragments) and most of the injected C reached the C^+ and higher states, and was then transported with high efficiency by the fast SOL flow down into the inner divertor. Thus, so far as being a source of carbon which ends up in co-deposition trapping of H/D/T in the inner divertor – such wall chemical sources can, unfortunately, be quite efficient.

Conclusion

The molecular breakup of CH_4 injected in a toroidally symmetrical way into the main SOL of DIII-D, at a location far from the divertor, has been modeled using the interpretive DIVIMP-HC (OEDGE) code, to extract information from spectroscopic measurements – toroidal cameras, filterscopes and CER – on the SOL (effective) parallel flow speed, the efficiency of carbon contamination of the main plasma and the efficiency of creating carbon co-deposits in the inner divertor. Such chemical wall sources of carbon can be fairly well shielded from contaminating the confined plasma, but the fast parallel flow, together with the rather small prompt local loss (by neutral fragment deposition near the CH_4 entry into the plasma) means that such sources can be rather efficient at creating carbon H/D/T co-deposits in the inner divertor, in confirmation of the experimental findings in JET [3] and DIII-D [2].

Acknowledgements

The authors would like to acknowledge the support of a Collaborative Research Opportunities Grant from the Natural Sciences and Engineering Research Council of Canada and the U.S. D.O.E.

References

1. Strachan, J.D., et al. Nucl Fusion, 43 (2003) 922.
2. Allen, S, this Conference
3. J.P. Coad, et al, JNM 290-293 (2001) 224.
4. P.C. Stangeby et al, JNM 313-316 (2003) 883.
5. McLean, A.G., MASc Thesis, University of Toronto, 2003.
6. W. Wampler, this Conference
7. J. D. Elder, this Conference
8. A. B. Ehrhardt and W.D. Langer, "Collisional processes of hydrocarbons in hydrogen plasmas", PPPL-2477, Sept 1987.

9. R. K. Janev and D. Reiter, J Nucl Mater 313-316 (2003) 1202.
10. S. K. Erents, et al, Plasma Phys. Control. Fusion 42 (2000) 905.
11. N. Asakura, et al, J Nucl Mater 313-316 (2003) 820.
12. B. LaBombard, et al, J Nucl Mater 313-316 (2003) 995.
13. W.P. West, et al, J Nucl Mater 313-316 (2003) 1211.

Figures

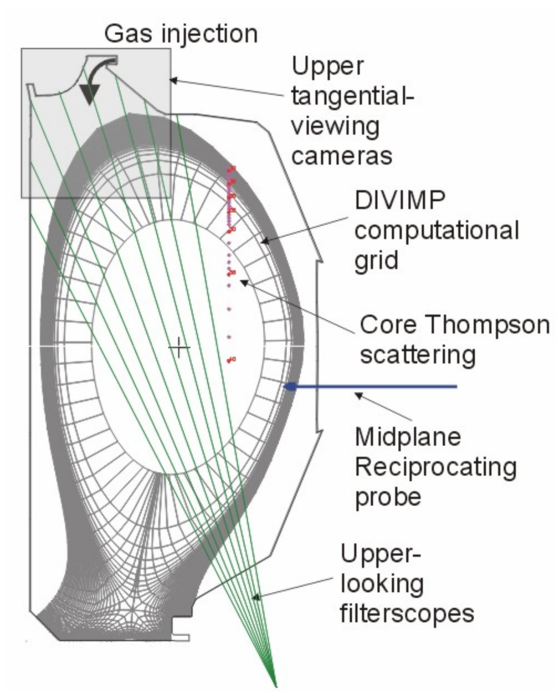


Fig 1. Gas injection arrangement and diagnostics used.

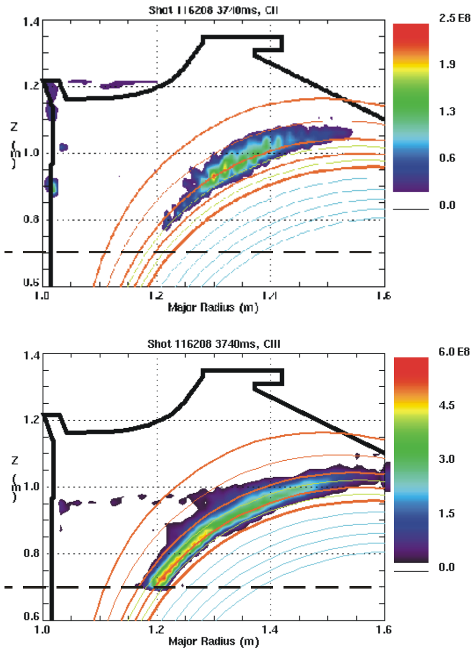


Fig. 2 Reconstructed 2D pictures from the toroidal viewing camera, in CII (above) and CIII (below).

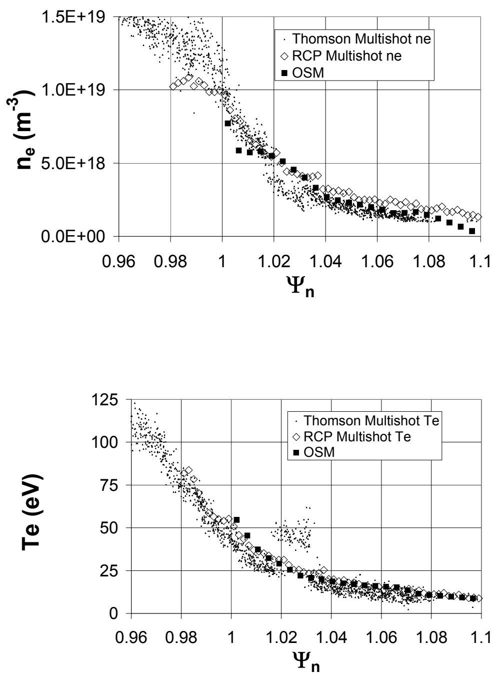
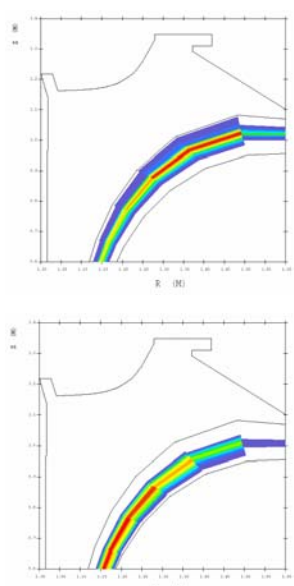


Fig. 3 Profiles of n_e and T_e in the SOL.



4. Code calculated CII and CIII 'clouds', to be compared with Fig. 2. Case of $M_{\|}$ = 0.4 and $D_{\perp}$ = 0.3 m^2/s.

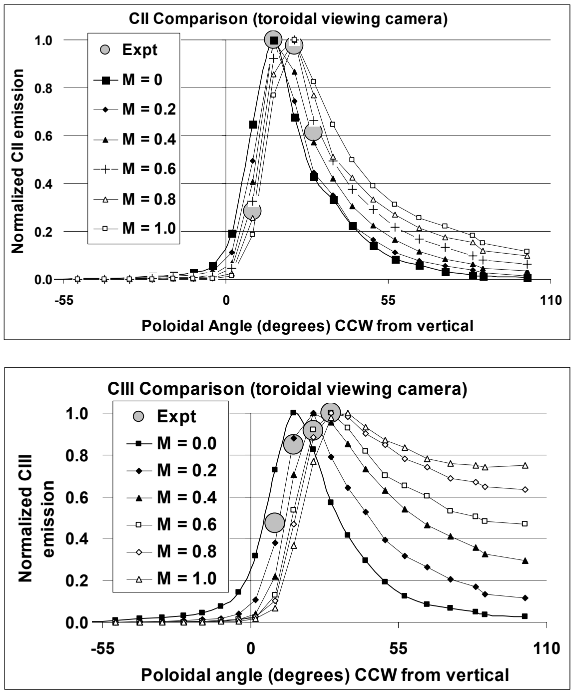


Fig 5. Comparison of CII and CIII poloidal profiles taken from the 2D reconstructions of the toroidally viewing camera, and code results assuming different values of $M_{\|}$. $D_{\perp} = 0.3\ m^2/s$. All profiles normalized to unity at peak.

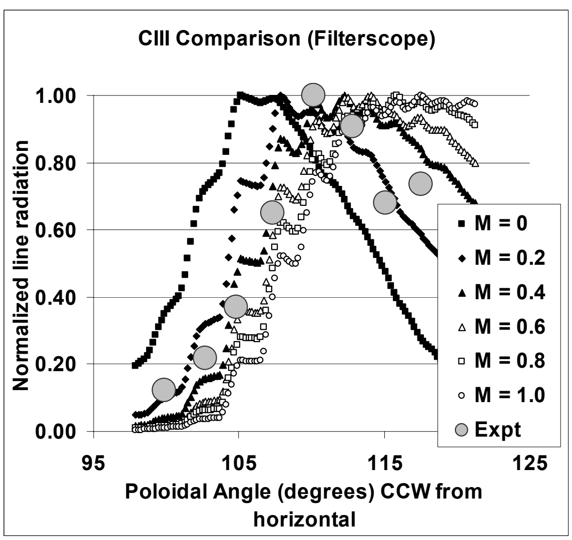


Fig. 6 Comparison of poloidal profile of CIII measured by the upward-looking Filterscope, compared with code results based on various parallel Mach Numbers. $D_{\perp} = 0.3\ m^2/s$. All profiles normalized to unity at peak.

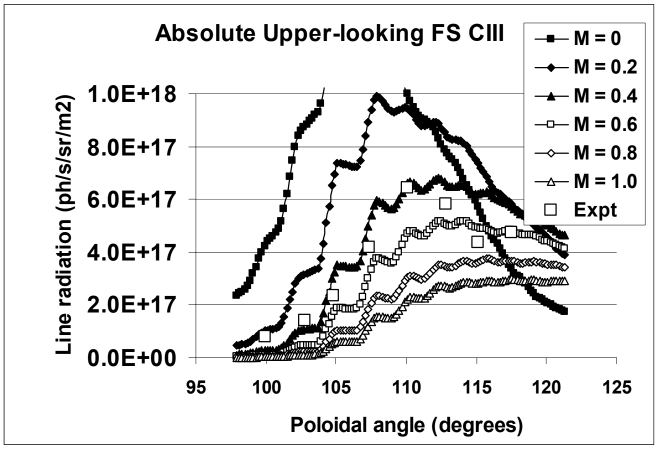


Fig. 7 Absolutely calibrated comparison of FS CIII and code results.

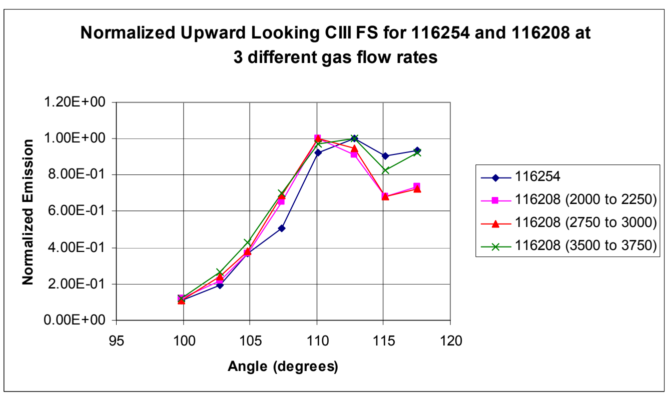


Fig. 8 Poloidal profiles of Filterscope CIII emission for 3 different CH_4 injection rates.

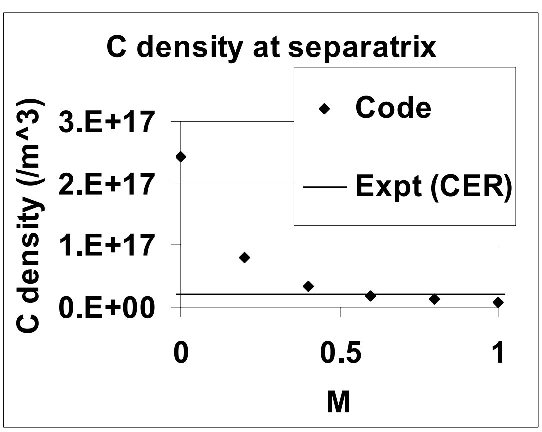


Fig. 9 Carbon density at the separatrix calculated by the code, compared with the CER measured value. Code used $D_\perp = 0.3\ m^2/s$.