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Spectroscopic characterization and simulation of chemical sputtering using the DiMES porous plug injector in DIII-D

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Abstract

A self-contained gas injection system for the Divertor Material Evaluation System (DiMES) on DIII-D has been employed for *in situ* study of chemical erosion in the tokamak divertor environment. The porous plug injector (PPI) releases methane into the plasma at a controlled rate through a porous graphite surface flush to a tile. In this way, the perturbation to the local plasma can be minimized, while also simulating the immediate environment of methane molecules released from a solid graphite surface. Photon efficiencies of CH_4 for measured local plasma conditions are reported. The contribution of chemical vs physical sputtering to the source of C^+ at the target can, in principle, be assessed through measurement of CII and CD/CH band emissions during release of CH_4 from the PPI, and due to intrinsic emission. These first results from this new experimental tool demonstrate the potential for the PPI to provide definitive results in future applications in DIII-D and indicate the improvements required to obtain firm quantitative conclusions.

Keywords: Carbon impurities; DIII-D; Hydrocarbons

1. Introduction

Carbon plasma facing components (PFCs) in a tokamak are subject to chemical erosion due to sputtering from hydrogenic impact. Although many laboratory-based measurements of erosion yields

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have been carried out, their applicability to the tokamak environment is uncertain due to mechanisms found only in tokamaks, such as prompt redeposition of dissociated hydrocarbon fragments. A number of methane injection experiments have been carried out on various tokamaks with gas injection using nozzles or tile gaps with gas puff rates significantly higher than that of intrinsic sources [1]. These macroscopic openings can be larger than the mean-free-path for deposition of the molecular fragments resulting from the break-up of the hydrocarbon molecules due to interaction with plasma electrons and ions. To better reproduce the immediate environment experienced by a hydrocarbon molecule released by chemical sputtering from an essentially continuous carbon surface, a porous plug injector (PPI) has been used to inject the hydrocarbon gas in these experiments. Such a spatially distributed injection of the gas should also be less disturbing to local plasma conditions than occurs with nozzle injection.

The primary goal of the PPI is to derive photon efficiencies for molecular and atomic species resulting from the breakup and ionization of products of chemical sputtering processes in the tokamak divertor. Methane only is considered here.

2. Experiment

The PPI is a self-contained gas injection system capable of puffing minute quantities of gas into the lower divertor of DIII-D (Fig. 1). Motivation and design of the PPI are discussed in [2]. The PPI was operated in DIII-D for one dedicated run-day and in several piggyback experiments. The dedicated day included 5 s exposures in 20 L-mode repeat discharges, 15 with gas puffing from the PPI. The gas used in the PPI was a 80%/20% mixture (by weight) of CH_4 and He. The latter was employed for *in situ* gas flow rate calibration by measurement of the 6680 Å HeI line intensity.

Each plasma shot included a three-step sweep of the outer strike point (OSP), each with a minimum 0.5 s dwell for diagnosis. Plasma conditions at the target were measured by Thomson scattering 1 cm above the divertor floor, ~40 cm toroidally away from DiMES and found to be, in attachment: $T_e = 22$ eV, $n_e = 2.5 \times 10^{19}$ m^{-3}; and in detachment: $T_e = 2.0$ eV, $n_e = 2.0 \times 10^{20}$ m^{-3}. No direct measurement of plasma conditions above the PPI was made in this initial experiment. Using laboratory chemical sputtering yields and target flux density

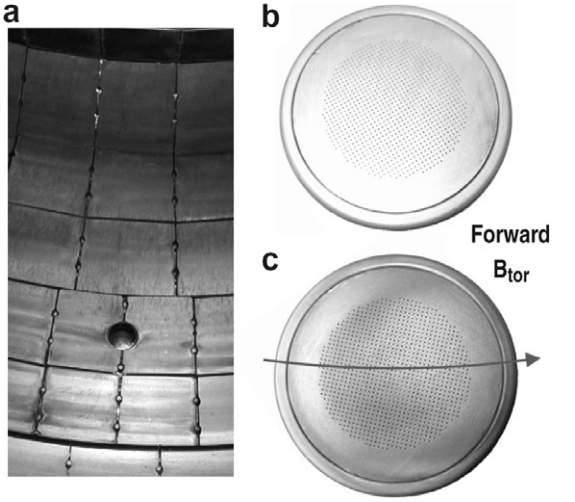

Fig. 1. (a) The lower divertor floor of DIII-D is shown, with the location of DiMES ($R \sim 1.5$ m) visible. When inserted, the PPI head is flush to the surrounding graphite tiles. The porous cap is shown in (b) before and (c) after plasma exposure in DIII-D.

$\Gamma_D^+ \sim 5 \times 10^{22}$ m^{-2} s^{-1}, measured in previous similar experiments, an anticipated carbon influx of $\Gamma_{c,in} \sim 1 \times 10^{21}$ m^{-2} s^{-1} is estimated, for a total release rate of $\sim 7 \times 10^{17}$ C/s over the surface area of the PPI, 7×10^{-4} m^2. The PPI injected methane at 1–50 times this carbon atom flux in its first application, reported here. The puff rate equal to the chemical sputtering rate is equivalent to ~2 standard cubic centimeters of CH_4 per minute (sccm), or 0.025 Torr l/s. Varying the gas puff rate allowed the degree of perturbation that the puff has on local plasma conditions to be determined, e.g. through identification of trends in spectroscopic emission data.

The main DIII-D diagnostics used included a high-resolution spectrometer (MDS), and the DiMES TV camera, both viewing the PPI almost directly from above. Langmuir probes, tangential cameras, filterscopes, divertor Thomson scattering, and an IR camera were also used.

3. Observations

The gas puff rate from the PPI was determined by a combination of *ex situ* calibration of the driving voltage, *in situ* calibration of gas canister pressure during controlled leak periods, and comparison of the derived flow rate to HeI emission during plasma operation. While the intention was to operate the PPI primarily with the (low) flow rates described

above, difficulties were encountered in controlling gas flow in a thermally variable environment. The flow rate was maintained as designed for a single shot only, then at 5–15× the targeted rate for 13 additional shots, and finally, at 50× the targeted rate for a single shot.

The MDS (spectral resolution $\Delta\lambda = 0.1$ Å, 80 Å bandwidth, 125 ms integration time) monitored HeI (6680 Å), CI (9100 Å), CII/C2 (5150 Å), and CD/CH/CII/D_γ (4300 Å). Simultaneous wide field (50×50 cm) coverage was provided by the DiMES TV camera monitoring equivalent emission lines. Simultaneous observation by MDS was made of the PPI and of a radially equivalent location separated toroidally from DiMES by 25 cm, allowing for a background subtraction from emission data at the PPI. Observations and analysis of CI emission from the PPI are discussed in [3]. Sample spectra from MDS viewing DiMES is shown in Fig. 2, demonstrating evolution from a CD-dominated Gerö band (CD $A^2\Delta \rightarrow X^2\Pi$ transition, bandhead at 4308 Å), to CH (bandhead at 4313 Å) at the onset of the PPI gas puff which approaches a release rate equal to ~1.5 times that of natural chemical sputtering.

While CD and CI emission due to the gas puff were observed not to extend much beyond the circle of the PPI head on the divertor floor, CII emission caused by the puff was found to extend well beyond the spatial extent of the PPI, preferentially downstream. Due to frictional drag of the flowing D-plasma on the C^+, the CII emission extended beyond the viewing circle of MDS (diameter of 2 cm), centered on PPI. To ensure that all CII photons were counted, the DiMES TV in CII was used to establish that the magnitude of the total CII emission was 2.3 (±0.3) times that collected by MDS.

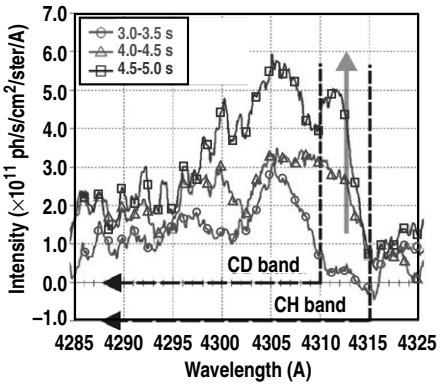

Fig. 2. Temporal evolution of CD/CH band structure from purely CD before onset of the PPI puff (4308 Å bandhead), then with increasing CH contribution (4313 Å bandhead) at the puffs initiation, and later in the puff as the gas flow is increased.

Substantial emission by the C_2 dimer Swan band ($d^3\Pi \rightarrow a^3\Pi_u$ transition, 5160 Å bandhead) due to the PPI puff was observed, despite the lack of C_xH_y, $x > 1$ in the injected gas. This has been reported previously by Brezinsek [5] and indicates significant interaction between the surface and redeposited fragments of the injected methane.

Initial examination of the CD/CH spectra produced by the PPI puff found no significant change in CD production as a consequence of CH_4 injection and breakup, indicating that the rate of H isotopic exchange with background D (D^+, recycled D^0, and D deposited in the surface) is lower than the film deposition rate from the injected CH_4.

4. Discussion

Simultaneous integration of the CD/CH band (4270–4315 Å) and CII (4267 Å) line for both emission from the PPI gas injection and for intrinsic background sources provides in principle a direct method for determination of relative contributions to the C^+-source by chemical and physical sputtering (Fig. 3) provided that the gas injection does not alter the local plasma conditions. In this analysis, the PPI imitates a purely chemically sputtered source, and thus the resulting CII to CH/CD emission signature is indicative of such a source. Note, that while in this study intrinsic chemical sputtering is mimicked for methane only, it is known that other hydrocarbons are released by chemical sputtering [4]. The measured relationship between integrated incremental CII and CD/CH intensity caused by methane injection is shown in Fig. 3(a). Data plotted represents emission due to the puff only, after subtraction of emission from intrinsic sources. The relationship between puff-only CII and CH/CD is found to be quite linear for all PPI puff rates, apparently an indication that the puff is not perturbative to the local plasma.

In Fig. 3(b), the intrinsic CII and CD emission from the location upstream of the PPI are shown overlaid with linear fits to PPI data indicating that roughly half (with large error bars) of CII, i.e. C^+-source, intrinsic to the OSP might be ascribed to chemical sputtering. As already noted, however, in this first application of the PPI, most of the puffing data in Fig. 3(a) were obtained for higher injection rates than planned, and there is paucity of data in the low flow region needed to support definitive

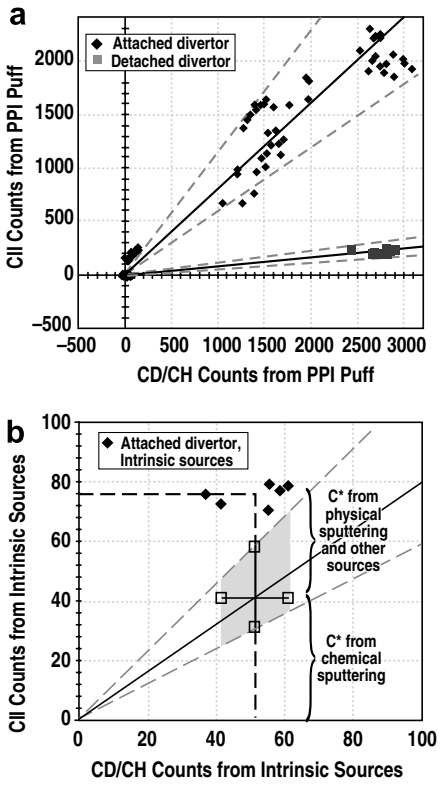

Fig. 3. (a) Incremental CII vs CD/CH integrated emission counts for all PPI gas puff data after subtraction of intrinsic sputtering sources at the OSP as measured away from the PPI. Data from five shots with an attached OSP and one with a detached OSP are shown. Best and bounding linear fits are shown for both cases. (b) CII vs CD integrated emission counts are shown, now for intrinsic sources only (at the OSP, but far from the PPI). Data for each shot are averaged over the full OSP dwell. Linear fits to PPI data in attached conditions from (a) are overlaid. In principle, the contribution of chemical sputtering to the intrinsic C-ion source can be estimated as equaling the fraction of the vertical distance to the group of CII points, at 70–80 counts (for the attached data), given by where the vertical line cuts the oblique line, thus ~50% for attached conditions. As discussed in the text, however, errors and uncertainties in the present system do not as yet permit such quantitative conclusions.

conclusions. Also, from Fig. 2 it appears that the detection threshold of the present MDS detector is too high to be able to record adequately defined CD/CH band spectra, at least for the intrinsic and low puff rate emissions, which are the critical data. This is a likely reason why the data at low gas injection rates exhibits an offset in CII vs CH/CD counts not suggested by higher puff datapoints. This also introduces further uncertainty to the interpretation of Fig. 3(b). In future studies a 4X more sensitive MDS detector will be used to address this problem. In a detached target, available PPI data are limited to a single shot, however, it is clear that the contribution of chemical sputtering to the C^+-source in this condition is smaller. Potential sources of error in this measurement include uncertainties in the PPI gas flow rate, an accurate background subtraction over the broad CD/CH spectra, full accounting of CII emission due to the puff which extends well beyond the PPI head, and a high photon detection threshold on MDS. The combined influence of these uncertainties prevents any firm quantitative conclusion from this initial experiment regarding the contribution of chemical sputtering to the C^+-source, but based on planned improvements, including a flow restrictor allowing precise flow rate determination and a built-in Langmuir probe to monitor possible local perturbation due to the puff, the next application of this method is expected to achieve quantitative estimates.

Contamination of the CD/CH band spectrum by lines of D_2 ($3D'\Pi \rightarrow 2P'\Sigma$ transition) as identified by Brezinsek [5] and in DIII-D [6] is not enhanced by the methane puff and was found to be a minor constituent compared to experimental error in measurement of the integrated CD/CH emission in PPI data.

It may be noted that the relative contributions of physical and chemical sputtering to the C-*atom* source entering the plasma has to be assessed separately. This will require carefully matched measurements of the CD and CI emission, which was not attempted in the present study, but will be one of the aims of future experiments.

Knowledge of photon flux specific to the local plasma conditions, $\phi(n_e, T_e)$, for each fragmented species monitored by MDS allows determination of *molecular photon efficiencies*, D/XB. For attached plasma conditions investigated here: $[D/XB]^{CH_4\rightarrow CH}_{A\rightarrow X,426.0\text{–}431.5\ nm} = 71 \pm 20$, $[D/XB]^{CH_4\rightarrow CI}_{902\text{–}911\ nm} = 63 \pm 20$, $[D/XB]^{CH_4\rightarrow CH}_{514.3\ nm} = 27 \pm 10$. In detachment, the D/XB increased to $[D/XB]^{CH_4\rightarrow CH,\ det}_{A\rightarrow X,426.0\text{–}431.5\ nm} = 177 \pm 45$. The value of effective D/XB for CH_4 has been previously reported using puffed injection through nozzles or tile cracks in attached divertor conditions similar to the present analysis by Poschenreider as ~110 (without distinction between CH_4 and CD_4) [7], and by Stamp as $\sim 140 \pm 25$ (into a hydrogen plasma) [8]. The value for CD_4 has been previously reported by Stamp as $\sim 80 \pm 25$ [8], by Monk as ~50 [9] and by Huber as $\sim 80 \pm 20$ [10]. Data for CD_4 is also well summarized by Philipps [1] and Brezinsek [11].

Production efficiency for each monitored species above may also be derived from knowledge of the rate of molecular injection for each shot and direct *S*/*XB* values for CI and CII at local plasma conditions from ADAS, and from HYDKIN for CH [12]. For attached conditions: $\Gamma_{CH}/\Gamma_{CH_4} = 0.29 \pm 0.10$, $\Gamma_{C^0}/\Gamma_{CH_4} = 0.48 \pm 0.15$, $\Gamma_{C^+}/\Gamma_{CH_4} = 0.44 \pm 0.10$; in detachment production efficiency for CH was much reduced: $\Gamma_{CH}/\Gamma_{CH_4} = 0.010 \pm 0.003$.

5. Conclusions

The DiMES porous plug injector has been demonstrated to be a potentially useful diagnostic instrument for study of plasma–surface interaction phenomena in the DIII-D divertor. Data from this first use of the PPI indicate that this diagnostic has the potential of providing definitive information on the role of chemical sputtering, as a contributor to C-atom and C^+-ion sources entering the divertor plasma.

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