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MEASUREMENT OF C I KINETIC TEMPERATURE IN METHANE PUFFING EXPERIMENTS ON DIII-D AND IMPLICATIONS FOR SPECTROSCOPICALLY DISTINGUISHING CARBON SPUTTERING MECHANISMS

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GENERAL ATOMICS

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ABSTRACT

Methane puffing experiments in DIII-D [A.G. McLean, et al., this conference] provide strong corroborating evidence for the assertion that plasma breakup of chemically sputtered, hydrocarbon molecules is responsible for the cold, near-symmetric C I line profiles observed in DIII-D's graphite-tiled divertor under low power, L-mode confinement conditions. This conclusion had been suggested by previous studies of divertor carbon sources in DIII-D based on atomic and molecular flux analysis, and on decomposition of the often asymmetric C I line shapes into thermal (Gaussian) and Thompson velocity distributions [R.C. Isler, et al., J. Nucl. Mater. **313-316**, 873 (2003); N.H. Brooks, et al., J. Nucl. Mater. **337-339**, 227 (2005)]. As divertor temperatures are raised by greater amounts of beam and RF heating, the increasingly asymmetric, shifted profiles of the C I line reveal the growing influence of physical sputtering. In low density, high-power H-mode discharges, the high energy, deuteron flux incident on divertor targets causes a dominance of physical sputtering over chemical.

I. INTRODUCTION

Puffing experiments recently conducted on the DIII-D tokamak provide a direct measurement of the velocity distribution of carbon atoms borne through plasma-induced breakup of methane molecules at the outer strike point (OSP) of the divertor and, also, in the scrape-off layer (SOL) surrounding the core plasma. Results from both of these puffing locations agree with the sub-eV temperatures reported some time ago for measurements in a localized methane puff through the face of a test limiter on TEXTOR [1]. However, these in-situ measurements disagree with the several eV effective temperature predicted by modeling of the chemical dynamics for fragmentation of the hydrocarbon molecules generated by chemical erosion of divertor tiles under the same plasma conditions [2]. Since the latter modeling results were used in Ref. [2] to interpret the fractional contributions to divertor erosion from physical and chemical sputtering, independent benchmarking of the modeling against measurements was warranted. This paper addresses the inconsistency in the neutral carbon, velocity distribution between the present measurements and previous modeling, and shows how the fractional contributions to divertor erosion from physical and chemical sputtering vary with plasma conditions.

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II. EXPERIMENTAL APPARATUS AND VIEWING GEOMETRY

Shown in Fig. 1(a) is a flux surface map of the lower single-null (LSN) magnetic configuration employed in localized methane puffing experiments into the divertor plasma of DIII-D. Ordinary $^{12}CH_4$ was puffed from a porous plug atop the DiMES translation mechanism at 150 degrees azimuth into the attached plasma at the foot of the outer divertor [3]. Superposed on this cross sectional view of the magnetic flux surfaces and the plasma boundary formed by the graphite armor on the vessel wall are the seven views into the lower divertor of the high-resolution, multichordal divertor spectrometer (MDS). In the plan view of Fig. 1(c), the viewspots are shown for the six, downward looking chords which intersect the tile-covered vessel floor. In addition to the six viewspots forming a two-piece radial line, a seventh viewspot is shown which lies at the same major radius as the porous plug, but counterclockwise from it. This view lies upstream of the plug, with respect to plasma flow toward the floor along the helical field lines of the outer leg. This upstream view is sufficiently far from 150 degrees azimuth that puffing through the plug exerted no influence over the emission seen on this chord.

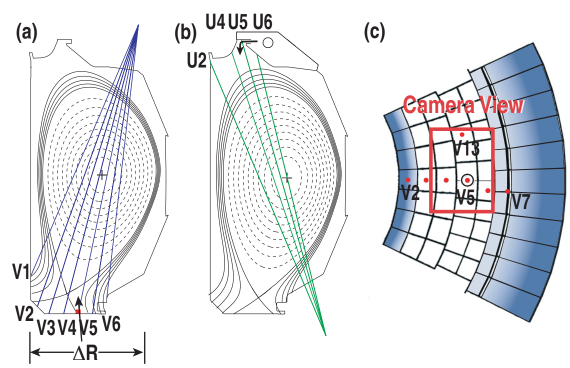

Fig. 1. Spectrometer views with LSN magnetic configurations employed for (a) localized gas injection from porous-plug located flush with floor tiles and (b) toroidally symmetric gas injection from upper, outer plenum. Dashed and solid lines in flux plots represent closed and open flux surfaces, respectively. (c) Plan view of spectrometer view spots in lower divertor for radial span ΔR indicated in (a).

In a separate experiment, methane containing the tracer element ^{13}C was puffed in a toroidally symmetric fashion from the upper outer baffle [4] into the crown of a high density, high power, ELMing H-mode plasma. Figure 1(b) shows the different LSN configuration used in this experiment, with the four upward-directed viewchords employed to measure neutral carbon emission in the upper SOL when methane was puffed from the upper baffle.

Signals are transported through 65 m long optical fibers to the MDS, a 1.3 m Czerny-Turner spectrometer equipped with 1200 line/mm grating. At the wavelength of the C I line used for the lineshape studies, 9094.829 Å, the dispersion is approximately 0.11 Å/pixel. Fourteen fibers are clamped in a line behind the straight entrance slit, thirteen coupled to views of the plasma and the fourteenth to an argon spectral lamp serving as a wavelength fiducial. The intensity distributions in a spectral window roughly 100-Å-wide were recorded simultaneously for the fourteen chords by a two-dimensional, charge-coupled device (CCD) with 22.5 μ pixels. An integration time of 100 ms was routinely used. The spectrometer entrance slits were set to a width of 20 μ in order to retain the capability for high-resolution, line-profile measurements. Although the input slit is straight, its image in the spectrometer exit plane is curved. Accurately accounting for this aberration caused by the spherical mirrors is crucial in calculating relative wavelength shifts in different channels. The offset due to image curvature between the center and end fibers in the 14-fiber, linear array can differ by as much as one pixel, which is more than the actual shift of the peak in the C I line caused by real physical processes under many conditions. The fiber-to-fiber offset associated with this curvature is 0.05-0.10 pixel widths, or approximately 0.005-0.010 Å.

III C I LINE PROFILE FROM METHANE BREAKUP AND TILE SPUTTERING

Methane was puffed continuously into the outer leg of low-density, L-mode plasmas which were heated with a single neutral beam source, square-wave modulated at 10% duty cycle (Fig. 2). From an initial position outboard of the porous plug early in the discharge, the outer strike point was swept inward and then held stationary at the radius of the plug from 2 s until the termination of beam heating at 5 s. Ion saturation current to the Langmuir probe at the plug radius and the divertor D_α intensity at the strike point radius remain constant during the strike point dwell. Divertor parameters of $n_e = 2.5 \times 10^{19}$ m^{-3} and $T_e = 23$ eV are measured with Thompson scattering above the strike point. Repeat discharges with the same plasma parameters were performed to obtain spectroscopic data at different gratings settings for the C I multiplet, and the CH and C_2 molecular bands.

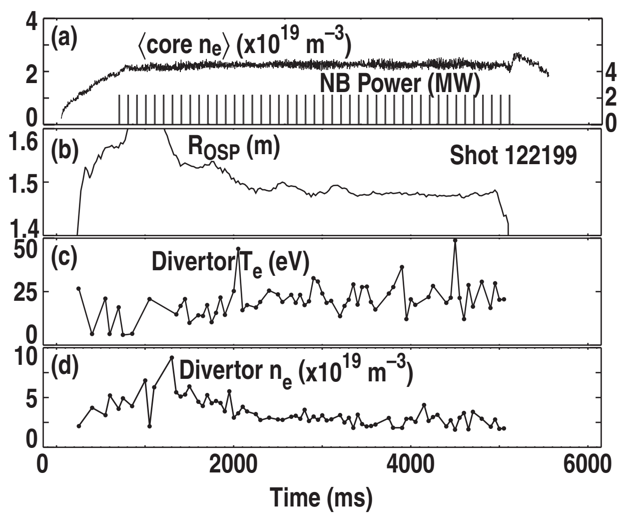

Fig. 2. Traces of representative plasma parameters for L-mode discharge used in porous plug experiments. (a) Line-averaged density of core plasma and modulated heating power with a single neutral beam source, (b) major radius of outer strike point, (c) divertor electron temperature measured with Thomson scattering diagnostic 6 cm above the porous plug, and (d) divertor electron density at the same location above plug.

The spatial patterns of neutral and ionic daughter species from the puffed methane were recorded with a CCD camera using bandpass spectral filters of 5-10 nm width to isolate their characteristic line or band emission (Fig. 3). Whereas C II exhibits a tail pointing in the downstream plasma direction, the images of C I and CH are circles centered over the porous area of the plug. This observation, taken alone, suggests that ionic intermediaries in the molecular breakup process are too short-lived for entrainment in the plasma flow toward the divertor target to elongate the spatial distribution of the neutral descendents C I and CH relative to the circular cross section of puffed gas. Application of the new Janev-Reiter database [5] to modeling of plasma fragmentation [6] leads, indeed, to lifetimes for the intermediate molecular ions which are 1/4 to 1/3 of those given by the older Ehrhardt-Langer database [7].

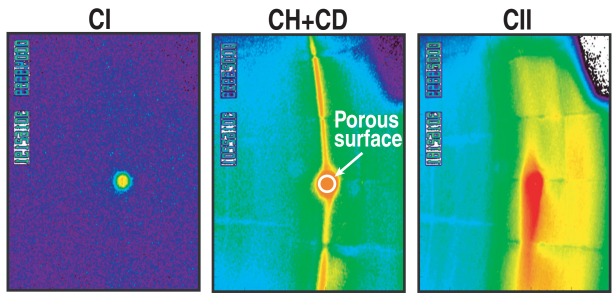

Fig. 3. Emission patterns of daughter species C I, CH and C II produced by chemical breakup of methane puffed through the porous plug. Spatial coverage of camera is depicted by dashed rectangle in Fig. 1(c). The signal through the C I filter exceeds the threshold for detection only over the porous plug, while those of CH and C II saturate over the plug. The CH filter passes CD as well, revealing chemical sputtering by incident deuterons elsewhere around the OSP ring. The color green in the images corresponds to an intensity roughly half that of the color red. The entire dynamic range of the VCR-recorded, CCD images is only about 7 bits.

The peak-normalized line profiles of the Zeeman-split C I 9095 line are compared in Fig. 4 for chord V5, looking into the puff, and chord V13, looking upstream from the puff. In addition, the instrumental profile measured with a low pressure, argon Geissler lamp is shown, as a fiducial for the rest wavelength and an indication of the instrumental profile. Here, the line profiles have been superposed after correcting for the wavelength offset associated with height of each viewchord's fiber along the spectrometer entrance slit. The central π-component of the C I line from the puff is only about 15% wider, measured at the half intensity point, than the instrumental profile. In contrast, the C I line from the view upstream of the puff location is distinctly broader on the blue side of the rest wavelength.

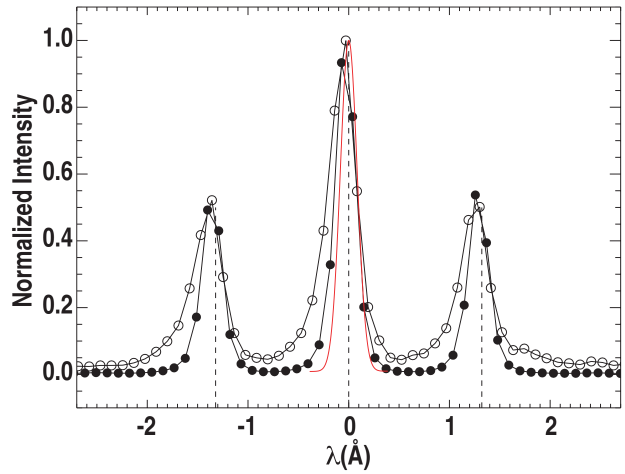

Fig. 4. Comparison in porous plug experiment of peak-normalized profiles for the Zeeman-split C I line with the instrumental profile. Solid circles are the data points from view chord V5, time-averaged over the strike point dwell period; open circles from view chord V13, similarly time-averaged. The red curve is the instrumental profile. All normalized data are superposed after correction for slit-height-dependent wavelength offset using the Ar I 9091 from an argon Geissler lamp coupled to the bottom most of the fibers dotted against the entrance slit.

The broadening of the C I line has also been studied during ^{13}C isotopic tracer experiments in which ^{13}C-labeled methane was injected in a toroidally symmetric fashion into the crown of high density, high-power ELMing H-mode discharges in the LSN configuration shown in Fig. 1(b). The signal enhancement to the C I line due to the toroidally symmetric puff is much smaller than that in the porous plug experiment, due to the non-localized nature of the puffing. Consequently, to see the effect of the puffing clearly, it is necessary to plot the difference in the signal during and before the puff. When this is done, it is seen that the width of the C I line emission from this non-localized puff source is, again, very little broadened compared to the instrumental profile.

In Fig. 5(a), the central π-component of the C I emission in the puff is modeled with a single Gaussian, following deconvolution of the instrumental profile using a maximum entropy method (MEM) [8]. Apart from a small discrepancy in the wings, the thermal distribution represented by the Gaussian gives an excellent fit to the source profile for an effective temperature of ~0.6 eV. Of course, because MEM deconvolution gives the simplest result compatible with experimental data, it can not reproduce the actual, jagged nature of the non-Maxwellian velocity distribution [5] imparted to the carbon atoms by the multiple Frank-Condon dissociation steps during the chemical breakup process. During the dwell, the temperature of the neutrals measured in the puff, shown in Fig. 5(b), is constant, except for two bumps early on, associated with small radial movements in the strike point.

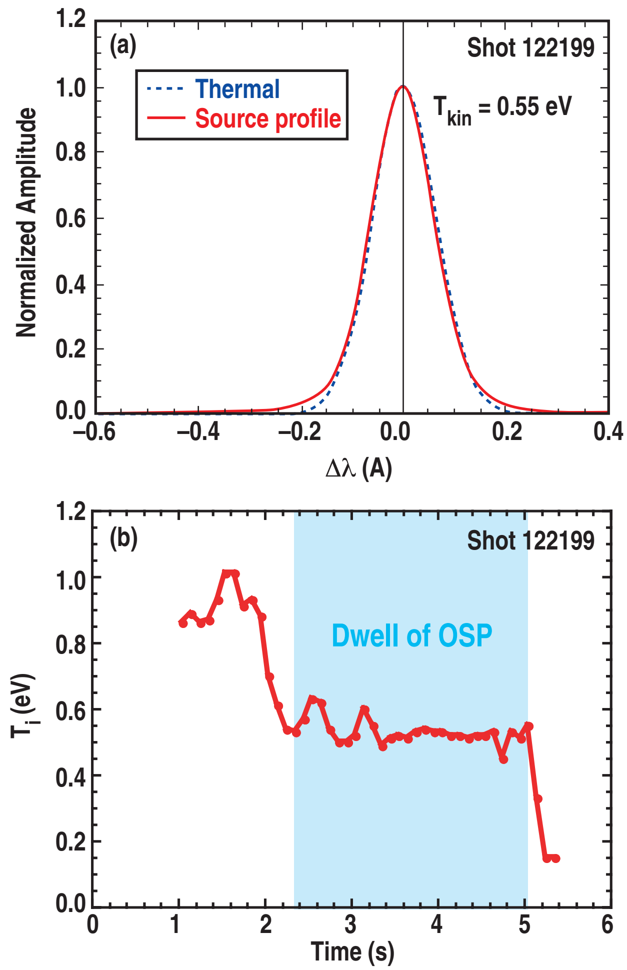

Fig. 5. (a) Best fit to the deconvolved source profile (solid line) of the Zeeman π-component from view V5 into puff from porous plug. A single Gaussian (dot-dash) provides a good fit, except in the far wings; (b) T_{kin} versus time for view V5.

Analysis of the C I emission from puffing in a toroidally symmetric fashion into the crown of a similar low-density, L-mode plasma, yields an effective temperature with a similarly low value. The analysis for these discharges is complicated by a small wavelength offset between the ^{13}C I and ^{12}C I lines. Since the toroidally distributed puff only doubles the C I emission from the far SOL along chord U5, the most reliable analysis was achieved by taking the difference of spectra during the puff and before the puff.

Figure 6(a) shows the C I source profile for chord 13, a view into a graphite tile upstream of the DiMES location. The very small blue shift in the peak of the source profile relative to the rest wavelength (between 0.03 and 0.04 Å) is an immediate indication that chemical sputtering predominates at the OSP in this low power, L-mode plasma. The best fit to the asymmetric profile is obtained for a mixture of chemical and physical sputtering profiles, with integrated intensities of the thermal and Thompson profiles in a ratio of 80:20. The Thompson profile corresponds to an impact energy of 150 eV for incident deuterons.

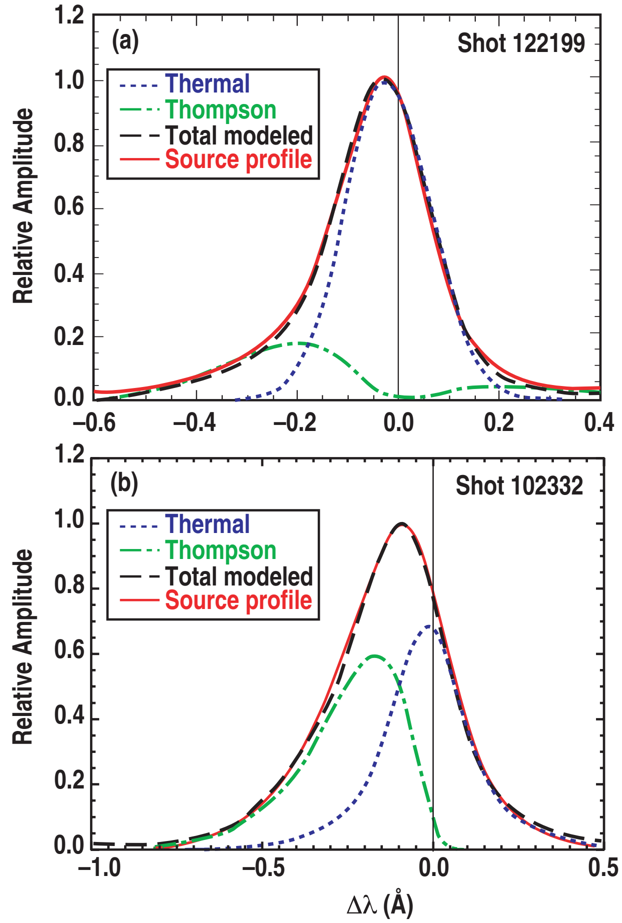

Fig. 6. Best fits to C I source profiles (solid lines) arising from divertor erosion of graphite tiles at the OSP. Modeled profile (long dash) is superposition of Thompson profile (short dash) and Gaussian (dot). (a) Low power, L-mode plasma on view 13, upstream of porous plug. (b) High-power, H-mode plasma with OSP in view of chord V6. Changed wavelength scale is necessary to show Thomson profile resulting from higher impact energy of incident ions.

In low-density plasmas with high levels of neutral beam heating, the increased temperature of the incident particles on the divertor targets lead to strongly asymmetric profiles which are clearly dominated by physical sputtering. The C I line source profile in Fig. 6(b) is from the upper inner strike point of a USN plasma with line averaged density of 4.5×10^{19} m^{-3} and neutral beam injection heating of 9.5 MW. The best fit for the Thompson profile corresponds to an impact energy of 270 eV. In this case, physical and chemical sputtering contribute about equally to the intensity.

IV SUMMARY

Methane puffing experiments have enabled the direct measurement in a tokamak of the neutral carbon velocity distribution resulting from plasma fragmentation of the volatile hydrocarbons characteristic of chemical sputtering. In CH_4 puffing experiments in the DIII-D divertor employing a porous plug, the measured C I line shape is well fit by a single Gaussian function with a full width half maximum corresponding to a kinetic temperature T_{kin} ~ 0.6 eV. Similarly low values of T_{kin} are observed when methane is puffed in a toroidally symmetric fashion into the crown of the core plasma. These T_{kin} measurements provide benchmarks for code modeling of the multi-step, chemical breakup process leading to free carbon atoms.

Divertor tile erosion is DIII-D is, in most cases, dominated by chemical and physical sputtering. At low divertor temperatures, C I line profiles tend to be symmetric about their intensity peaks and dominated by chemical sputtering. With ever larger amounts of beam heating, the CI line profile becomes increasingly asymmetric and blue-shifted, indicative of physical sputtering growing in relative importance compared with chemical.

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Acknowledgments

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