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Toroidally asymmetric distributions of hydrocarbon (CD) emission and chemical sputtering sources in DIII-D

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Abstract

Measurements in DIII-D show that the carbon chemical sputtering sources along the inner divertor and center post are toroidally periodic and highest at the upstream tile edge. Imaging with a tangentially viewing camera and visible spectroscopy were used to monitor the emission from molecular hydrocarbons (CH/CD) at 430.8 nm and deuterium neutrals in attached and partially detached divertors of low-confinement mode plasmas. In contrast to the toroidally periodic CD distribution, emission from deuterium neutrals was observed to be toroidally symmetric along the inner strike zone. The toroidal distribution of the measured tile surface temperature in the inner divertor correlates with that of the CD emission, suggesting larger parallel particle and heat fluxes to the upstream tile edge, either due to toroidal tile gaps or height steps between adjacent tiles.

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Keywords: Carbon chemical sputtering; CD imaging; CD spectroscopy; DIII-D

1. Introduction

Chemical sputtering of carbon by deuterium neutrals and ions is a critical issue in future long-pulse fusion devices with carbon plasma-facing components (PFCs), because of plasma contamination with carbon and tritium retention in the PFCs. Previously, a systematic study of the evolution of hydrocarbons released from the divertor in DIII-D [1], using carbon-deuteride (CD) emission spectroscopy [2] at the tile center, suggested a four-fold reduction of the chemical sputtering yield, Y_{chem}, over 10^5 s of plasma operations, and >30 boronizations. Recently, imaging of visible CD and thermal infrared (IR) emission in DIII-D showed that these emissions vary toroidally across the tiles in the lower divertor, with maxima at tile edges. These results initially suggested that the

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spatial temperature distribution is the primary cause of the spatially varying chemical sputtering sources, since Y_{chem} is a function of substrate surface temperature, typically increasing by a factor of 2 over the range from 20 °C to 100 °C [3]. Measurements in attached and partially detached divertor plasmas of well-diagnosed, low-confinement (L-mode) discharges in DIII-D indicated, however, that larger particle fluxes to tile edges give rise to enhanced recycling, and thus stronger chemical erosion of those surfaces. In this paper these experimental results are described and interpreted with the aid of other optical and plasma diagnostics.

2. Imaging and visible CD spectroscopy in DIII-D low-density L-mode plasmas

2.1. Description of the experiments and diagnostics

The spatial intensity distributions of deuterium and carbon line emission, and molecular hydrocarbon emission in the lower DIII-D divertor were characterized in low-density ($n/n_{GW} \sim 0.25$), lower single-null L-mode discharges. They were carried out at a plasma current (I_p) of 1.1 MA with the toroidal field (B_T) of 2 T in forward and reversed directions, corresponding to the ion $B \times \nabla B$ drift into and out of the divertor, respectively. Neutral beam blips of 10 ms duration were injected every 100 ms to facilitate charge-exchange spectroscopy measurements of the fully stripped carbon density at the outer midplane, while simultaneously keeping the plasma in L-mode. In both B_T configurations Thomson scattering measurements yielded the electron density (n_e) and temperature (T_e) at the upstream separatrix of $\sim 8 \times 10^{18}\ m^{-3}$ and 40 eV, respectively. These upstream conditions produced a low-recycling plasma in the outer divertor leg, with T_e of 20 eV at the separatrix of the outer target plate, independent of B_T as measured with Langmuir probes. At the inner divertor reversing B_T did change the plasma conditions from partially detached in forward B_T to attached in reversed B_T, with $T_{e,sep}$ rising from <5 eV in forward B_T to 15 eV in reversed B_T configuration. A similar change in the inner divertor conditions was reported from a number of experiments [4–6], including DIII-D [7], and is generally attributed to the change of the $E \times B$ drift direction in the private flux region. The change in the inner divertor conditions was also measured by toroidally viewing cameras, which showed for the forward B_T case an increase in the D_α recycling flux by a factor of 2, and a shift of the carbon emission (CII 514.7 nm) away from the target plate.

The spatial distributions of the CD and D_γ emissions in the lower divertor were measured with an intensified charge-injection device (CID) camera in a tangential viewing geometry [8]. This camera provides a toroidal field-of-view of ~70° along the inner and outer divertor (Fig. 1(a)); it uses narrow band-pass filters of 1.0 nm and 3.0 nm to isolate the CD $A^2\Delta - X^2\Sigma$ electronic resonance band at 430.8 nm and D_γ, respectively. The spatial resolution of the imaging system is a function of the toroidal angle. At the plane-of-tangency with the center post it is approximately 0.5 cm. The camera measurements were complemented by two visible spectrometers with a vertical viewing geometry of the lower divertor region. The multi-chord divertor

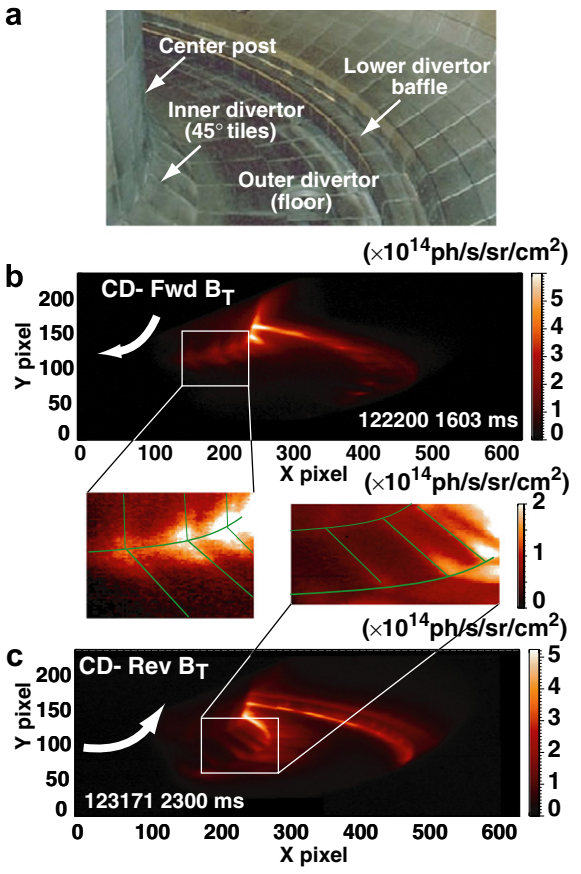

Fig. 1. Approximate viewing geometry of the DIII-D lower divertor tangential camera (a), and spatial distribution profiles of the CD emission in (b) forward and (c) reversed B_T configuration. The inserts give a magnified view of the inner divertor (45° tiles) region. The green grid lines illustrate the locations of tile gaps.

spectrometer MDS is a high-resolution instrument (resolution 0.01 nm) and has a sensitivity of 10^{11} ph/s/sr/cm^2/nm. The Reticon system is a medium-resolution (0.1 nm) spectrometer; it uses an intensified detector, and has a single line-of-sight of the outer divertor region. Consistency checks between the camera and spectrometer intensity calibrations were performed using methane injection through a porous plug injector [9].

2.2. Toroidal profiles in forward and reversed B_T configurations

The CD emission profiles obtained along the 45° tiles of the inner divertor (Fig. 1(a)) are toroidally periodic and show maxima at the upstream surface of each tile (Fig. 1(b) and (c)). Toroidal emission profiles were measured for given radial locations on the 45° tiles (Fig. 2(a) and (b)), which show that the CD emission peaks near the edge of the adjacent tile downstream of the tile gap. Within the limited spatial resolution of the camera system, it is impossible to distinguish weather the peak of the emission is right at the edge of the tile or on the tile surface. Further uncertainty was introduced by the alignment of the images with the DIII-D vacuum vessel, which was obtained from images taken during abnormal plasma events, such as large disruptions, when the vessel was illuminated. Less variation of the CD emission was generally observed along the outer strike zone, due to the more shallow viewing geometry for this part of the vessel. However, with the outer strike on ports, or close to the lower outer baffle, significantly stronger CD emission was observed from port edges and the face of the baffle. A CMOS-type camera vertically viewing only the outer strike point region corroborates these results. Using this camera we observed enhanced CD emission around radial tile gaps, with nearly constant emission elsewhere across the tile surface.

For the same plasmas toroidally symmetric D_γ emission was observed along the inner strike zone in forward and reversed B_T configuration, while toroidally periodic D_γ profiles similar to those of CD were seen along the 45° tiles in reversed B_T configuration (Fig. 2). The D_α and D_γ emission profiles were consistently toroidally symmetric along the inner strike zone, however, the partially detached plasma conditions in the inner divertor lead to 2–3-fold stronger neutral deuterium emission in forward B_T than in reversed B_T configuration. Spectral contamination is an issue when measuring

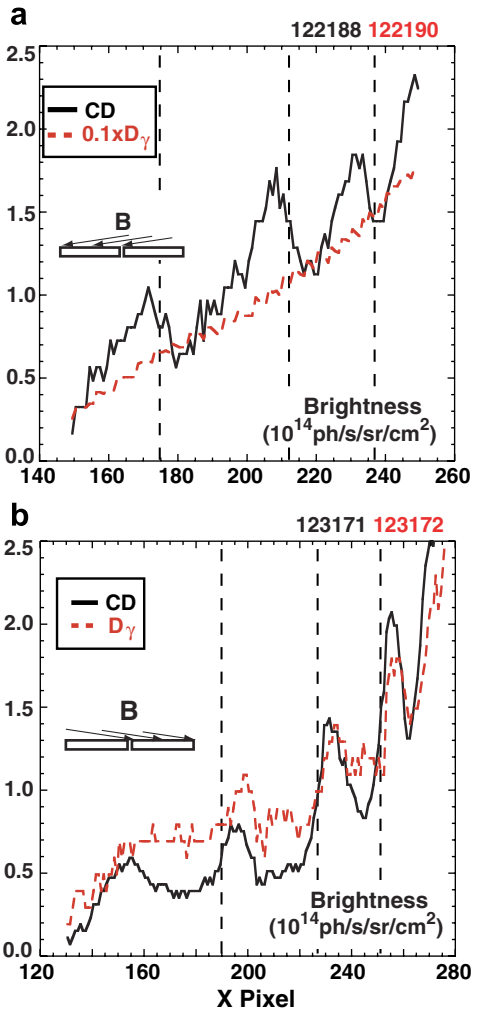

Fig. 2. Toroidal CD and D_γ emission profile along the inner divertor (45° tiles) obtained in forward (a) and reversed (b) B_T configuration. In forward B_T the profile was taken at radial location $R = 1.03$ m, in reversed B_T at $R = 1.14$ m, leading to slightly different locations of the tile gaps (vertical lines) on the (X, Y) image grid. The inserts show the alignment of the (total) magnetic field vector, B, with respect to the tile surface.

neighboring lines or bands with insufficiently narrow band-pass filters, or if one neighboring spectral region is significantly brighter than the one of interest. This could affect the CD emission measured in forward B_T discharges, since the D_γ emission along the inner divertor is an order of magnitude stronger than CD, as well as the D_γ line emission measured radially inboard of the inner strike point at the 45° tiles in reversed B_T.

Using the MDS spectrometer, the CH/CD band was well observed at the outer strike zone when methane was puffed through the porous plug, and barely above background in discharges without

CH_4 injection. One view chord of the MDS system was aligned with the porous plug head, while others viewed the inner strike zone, the private flux region, and the outer baffle region. The MDS view chords are 2 cm in diameter, centered on each tile viewed. In comparison, the average dimensions of tiles along the floor and 45° tiles are 16.5 cm × 14.5 cm (toroidal × radial). The spectroscopic brightness at the D_γ line convolved with the camera D_γ filter transmission curve is consistent with the photometric measurements from the camera within the uncertainty of both measurements. The more sensitive Reticon system, on the other hand, detected the CH/CD band head at the outer strike point region during the methane puff as well as without the injection. In discharges without CH_4 puffing the filter-weighted brightness of the CD band observed with the Reticon system is approximately a factor 5 lower than measured with the cameras. The spectral range of the Reticon system, however, was insufficient to span the full CD $A^2\Delta - X^2\Sigma$ resonance band, explaining some of the discrepancy between spectrometer and camera measurements. Given the uncertainties due to differences in viewing geometry and limited spectrometer sensitivity, we estimated for the camera measurements a maximum spectral contamination of D_γ on CD of the order 10%. If the D_γ contribution were to be subtracted from the CD emission, this would yield even stronger peaking of the CD emission at the upstream tile surface along the inner divertor in forward B_T (Fig. 2(a)). Conversely, it is conceivable that the measured D_γ emission at the 45° tiles in reversed B_T was mostly caused by cross-talk from the CD band because of the 3.0 nm band-pass filter used. A sufficiently sensitive spectrometer viewing the tile center and tile gap regions is necessary to conclusively resolve the issue of spectral contamination.

The surface temperature distribution measured with a vertically viewing IR camera [10] was found to be toroidally periodic along the inner divertor, in forward and reversed B_T configurations. The IR camera measures the thermal emission from the tiles over a wavelength range of 8–12 μm, thus avoiding spectral contamination with deuterium molecular bands at 2–3 μm [11]. In Ohmic and L-mode plasmas the measured surface temperatures (T_{surf}) are generally low, between 20 °C and 40 °C, varying from tile to tile as well as across individual tiles. As shown in Fig. 3, in these experiments T_{surf} peaks toroidally at the upstream surface of each tile, and decreases by ~3 °C toward the downstream edge.

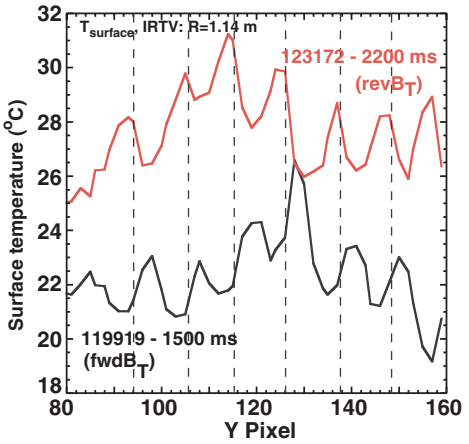

Fig. 3. Toroidal profiles of infra-red (IR) emission along the inner divertor (45° tiles) measured in forward (black) and reversed (red) B_T configuration. The radial profiles were taken at radial location $R = 1.14$ m. The vertical lines indicate tile gaps along the inner divertor.

3. Discussion

CD and IR imaging of the inner divertor region in DIII-D indicated that the plasma–surface interaction is strongest at the upstream edge of the tile surfaces independent of the toroidal field direction. Visible inspection of the graphite tiles during shutdown periods showed that tile edges are much more eroded than the tile centers; they are literally rounded off. Field lines typically graze the divertor tiles with an angle of 2–3°. Tile-to-tile gaps and tile misalignment can lead to nearly-normal incidence of the field lines onto the upstream side wall of tiles, and thus the particle and heat fluxes to a small area of the side wall can be 20–30 times higher than to the plasma-facing flat surface. Flat tiles installed on circular (center post) or conical (inner divertor 45°) surfaces lead to shadowing of the upstream edge of the adjacent tile that is in the B_T direction [12]. In such a situation one would expect stronger fluxes to the downstream tile surface, which is not seen experimentally. Slight tile misalignment and larger tile gaps along these surfaces can offset the effect of heat flux shadowing, and thus provide more heat to the upstream edge of some tiles. Since the ion Larmor radius is sub-millimeter for the magnetic fields in DIII-D, and typical SOL ion energies ($T_i =$ 10–30 eV), gyro-orbit effects are negligible.

Toroidal variations of the plasma conditions can produce different surface films on the plasma-facing tile surfaces, tile edges, and tile side walls, which

may contribute to the measured CD emission profiles. For a given temperature in the range observed in this study, Y_{chem} can vary by a factor of 5 between hard and soft amorphous carbon films [3]. Very little is known experimentally about these films, in particular in tile gaps, in the discharges described here, and detailed modeling of the dynamics of erosion, deposition, and re-erosion at gaps and tile edges is needed [13].

During the 2005–2006 DIII-D shutdown, the lower inner divertor (45° tiles) and the lowest three rows of the center post of flat tiles were replaced with contoured tiles to improve the toroidal uniformity of the target heat flux. Field line tracing showed that contouring of these tiles will lead to a twofold reduction of the peak heat load to the downstream end of tiles [12]. In addition, the reduction of the averaged gap size by a factor of 2 to approximately 1 mm, and leveling of the tiles to a fraction of 1 mm [14] will significantly contribute to producing toroidally more uniform fluxes to the target plate. The installation of virgin graphite (ATJ graphite) tiles provides a unique opportunity to monitor the long-term evolution of the hydrocarbon emission with diagnostics previously unavailable.

4. Summary

Spatial distribution profiles of molecular CD and thermal IR emissions measured in DIII-D with cameras indicate that the carbon chemical sputtering sources in the lower divertor is not axisymmetric, but concentrated near tile edges. Toroidally periodic emission profiles were obtained in lower single-null L-mode discharges along the inner (45°) divertor tiles, with the maximum emission measured near the upstream tile edge in forward and reversed toroidal field configurations. The temperature variation across tiles in the toroidal direction is small, at most 3 °C, thus the increase in the chemical sputtering source is likely to be due to increased particle fluxes to tile edges rather than a tile temperature effect. The toroidally periodic distribution of CD emission concentrated near tile edge along the 45° divertor tiles is consistent with low/negligible CD intensities measured by the MDS spectrometer viewing the tile centers. If spectral contamination of D_γ line emission on the CD measurement is significant, visible spectroscopy viewing the tile center only may underestimate the peak-to-valley CD band emission ratio by as much as an order of magnitude. Toroidally asymmetric CD emission profiles were also observed in partially detached, high-confinement (H-mode) discharges, and appear to correlate with the recycling flux distribution as measured by D_γ emission during ELMs.

Acknowledgements

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