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ABSTRACT

The evolution of carbon release from the DIII–D lower divertor tiles is studied using atomic and molecular spectroscopy. Newly installed virgin graphite tiles in 1992 are found to have had a chemical erosion yield, $Y_{chem} \leq 3\%–5\%$, consistent with both laboratory results and similar experiment in other tokamaks. The average Y_{chem} measured in the DIII–D lower divertor decreased approximately a factor of ten between 1992 and 2000. The presumed cause of this reduction is the cumulative effect of >30 wall-conditioning boronizations and 10^5 s of plasma exposure, although the relative importance of these two mechanisms is unknown. This result indicates that a substantial reduction in carbon chemical erosion, and its relative importance as a source of carbon, can be obtained by long-term *in-situ* wall conditioning techniques. The total carbon source sputtered into the DIII–D lower divertor has also apparently decreased over the same period. However, there has been no significant decrease in the average core carbon contamination with the decreasing lower divertor carbon source.

Keywords: Carbon, chemical erosion, divertor

1. INTRODUCTION

The control of carbon erosion is important in optimizing the performance of current and future confinement devices. Contradictory evidence on the relative importance of carbon chemical and physical erosion has been found in experiments and modeling on the all-graphite DIII–D tokamak. Experiments using helium plasmas [1] and modeling with the multi-fluid UEDGE code [2] suggest that chemical erosion is important for contaminating the core plasma. Conversely, recent carbon erosion experiments [3,4] and hydrocarbon molecular spectroscopy, which focus on the open geometry DIII–D lower divertor, indicate that chemical erosion is much weaker than expected from laboratory chemical yield measurements. In particular, divertor chemical erosion seems to be minimal when the divertor plasma is detached — a plasma state characterized by low temperature ($T_e < 2$ eV), high density and particle flux ($n_e > 10^{20}$ m^{-3}, $\Gamma \sim 10^{23}$ s^{-1}m^{-2}) — where chemical erosion should be the dominant erosion mechanism. These studies are complicated by the many dependencies of chemical erosion yield with plasma and surface parameters [5].

A comprehensive spectroscopic survey has been performed in order to better illuminate the mechanisms that could be responsible for the above observations. The principal result of the spectroscopy survey is that the chemical erosion rate of carbon from the DIII–D lower divertor graphite tiles has evolved, gradually decreasing over the eight years since their installation in 1992. Therefore, it appears that the relative importance of chemical erosion as a carbon source in the lower divertor is not constant. Separately, no appreciable decrease in the core plasma carbon contamination has been found with decreasing divertor carbon source.

2. EXPERIMENTAL RESULTS

2.1. HISTORY OF DIII–D CARBON TILES

The DIII–D tokamak converted to 100% graphite coverage of all plasma-facing surfaces in the fall of 1992 (approximately shot #76700). Exposed graphite tile surfaces (which covered ~40% of the wall in the previous configuration) were thoroughly cleaned and re-installed. Baking and grit-blast cleaning removed all hydrogenic gas and metal contaminants from the tiles [6]. Therefore, the DIII–D wall can be considered 100% “virgin” carbon surfaces starting with the 1993 plasma operation period. No significant modification or tile removal has subsequently occurred in the lower divertor.

Significant conditioning in the form of plasma exposure and boronization has been applied over the lifetime of the DIII–D tiles. Since 1992, approximately 25,000 plasma discharges have occurred, for an accumulated plasma exposure time ~10^5 s. DIII–D operates with a large variety of magnetic geometries, resulting in high power-density strikepoint exposure over the entire lower divertor surface. As of May 2000, ~30 boronization films, each ~ 100–150 nm in thickness, have been applied on DIII–D [7], resulting in a cumulative boron layer ~ 3–5 µm. The boron is eroded and redistributed by plasma exposure, but remains as part of the DIII–D wall. Vacuum conditioning and boronization use vessel walls heated to 300–400°C. DIII–D plasma operations occur with no active heating or cooling of the graphite tiles.

2.2. DIAGNOSTICS

The principal spectroscopy diagnostic used in the survey is the multi-chord divertor spectrometer (MDS). MDS consists of a 1.3 m visible spectrometer coupled to a fiber optic-lens assembly that provides fixed viewing chords that span the radial extent (R = 1.0–1.7 m) of the open DIII–D lower divertor with ~20 mm spatial resolution [8]. The spectrometer has been equipped with several different gratings and detectors since 1992. *In-situ* photometric calibrations are only available for the current CCD camera detector configuration (since 1997).

Core plasma contamination is determined from visible charge-exchange recombination (CER) spectroscopy of carbon (CVI 5290 Å, n = 8-7) [9,10]. The viewing chord used in this study measures carbon density (n_C) and concentration ($f_C = n_C/n_e$) at normalized radius r/a ~ 0.7-0.8. This is a suitable radial location to indicate "global" core plasma contamination, since it is far enough inside the separatrix that carbon is fully ionized, yet measures f_C on flux surfaces that represent a large part of the plasma volume. Additional spectroscopic coverage of the core plasma is provided by a survey (100–1100 Å) vacuum ultra-violet spectrometer (SPRED), which has a midplane line of sight with a tangency point near the magnetic axis (R = 1.8 m). Hence low charge states of carbon and recycling deuterium entering the core edge plasma are measured with SPRED.

2.3. SPECTROSCOPIC INTERPRETATION OF EROSION

A relative measurement of chemical erosion yield, Y_{chem}, at the divertor can be obtained from the ratio of hydrocarbon molecular brightness to deuterium recycling brightness. This is based on the assumption that deuterium is a nearly perfect recycling species, therefore the local D neutral brightness (or photon flux) B_D is related to the incident plasma flux (Γ_{D_+}). Similarly, the photon flux measured from the hydrocarbon CD molecule radical (B_{CD}, $A^2\Delta$-$X^2\Pi$ (0–0) at 4308 Å) is a relative indication of carbon molecular flux ($\Gamma_{C_xD_y}$) chemically eroded from the plate. The specific ratio used in this study is,

$$Y_{chem} = \frac{\Gamma_{C_xD_y}}{\Gamma_{D^+}} = \frac{B_{CD} \cdot (D/XB)_{CD_4}}{B_{D_\gamma} \cdot (S/XB)_{D_\gamma}} \propto \frac{B_{CD}}{B_{D_\gamma}} \quad , \tag{1}$$

where $B_{D\gamma}$ is the brightness of the n = 5–2 deuterium Balmer line (4339 Å), and (D/XB)/(S/XB) are the dissociations/ionizations per photon ratios for the respective transitions [11]. In a similar fashion, a measure of the total carbon release from the plate into the divertor is obtained from the ratio of singly ionized carbon brightness (B_{CII}) to recycling emission. Specifically,

$$Y_{C,total} = \frac{\Gamma_{C^{+1}}}{\Gamma_{D^{+}}} = \frac{B_{CII} \cdot (S/XB)_{CII}}{B_{D} \cdot (S/XB)_{D}} \propto \frac{B_{CII}}{B_{D}} \quad , \qquad (2)$$

where S/XB is again the ionizations per photon ratio for the specific transitions. For this study two pairs of carbon/deuterium lines are used in the divertor: CII (4268 Å) to D_γ (4339 Å) and CII (6578 Å) to D_α (n=3-2, 6561 Å).

The choice of adjacent wavelength transitions is critical for this study. First, it eliminates the need to know the history of the absolute photometric calibration, which is unknown for the MDS spectrometer. Secondly, spectra obtained simultaneously eliminate the need for repeated discharges with identical time histories and plasma parameters.

These “loss events” per photon ratios (S/XB, D/XB) allow one to relate the measured photon flux back to an original particle flux and are determined by the details of the species’ atomic/molecular rates, the plasma parameters and the viewing geometry. An important assumption in this technique is that all loss events take place within the viewing volume. Therefore, this yield measurement technique is most appropriate in divertor regions of high plasma density, where ionization/dissociation mean free-paths are relatively short (< 10 mm). Even this case is complicated by the possible loss of C^{+1} and hydrocarbon ions through redeposition. Obviously more sophisticated modeling is necessary to obtain absolute yields. Nevertheless, restricting analysis to strikepoint locations ensures that measured emissions from molecules and low charge states of carbon are dominated by that portion of the viewing chord close to the target plate.

With measured plasma parameters, the relative yield comparison can be converted into an absolute erosion yield with a knowledge of the D/XB and S/XB values, which are summarized for typical attached divertor plasma conditions found in the DIII–D outer divertor leg in Table 1. S/XB values are obtained from a collisional-radiative atomic rate package [12] and have been

Table 1
Calculated and measured (S/XB) and (D/XB) values for relevant transitions for attached plasma (T_e = 20 eV, n_e = 2-5x10^{19} m^{-3}). * symbol indicates value verified by DIII–D experiments

$(S/XB)_{D\gamma}$ 4339 Å	$(D/XB)_{C^+}$ 4308 Å	$(D/XB)_{CD_4}$ 4308 Å	$(S/XB)_{CII}$ 4268 Å	$(S/XB)_{D\alpha}$ 6561 Å	$(S/XB)_{CII}$ 6580 Å
~1–2×10^3 *	10	~50	~30	20–40 *	10

verified by calibrated MDS measurements near the outer strikepoint (OSP) for deuterium Balmer lines. The $(D/XB)_{CD_4}$ relates CD band emission to eroded methane (CD_4) in order to estimate chemical erosion yield and is derived from both experiment [13] and modeling [14]. The $(D/XB)_{C^+}$ relates the contribution of the measured CD radical to direct carbon ionization and is calculated from [15].

2.4. SURVEY OF LOWER DIVERTOR CARBON EROSION

A spectroscopic survey has been compiled that includes all discharges between 1992 and 2000 where relevant lower divertor spectroscopy (MDS) data were available. Samplings of MDS data taken since January 2000 are also included. Although this constitutes a relatively small number of discharges (< 100), the survey presents a good sampling of shapes, core plasma parameters and confinement. Since DIII–D runs principally in H–mode, this confinement mode will be the focus of the survey, in order to provide the maximum amount of data. No systematic drift in plasma parameters is found for the ELMy H–mode shots in the survey between 1992 (shot number #75000) to 2000 (~#102000), with average values being indicative of core plasma parameters [Fig. 1(a)]. Only discharges occurring > 50 discharges after a boronization are included in order to eliminate the measured temporary reductions in carbon erosion caused by the boron layer.

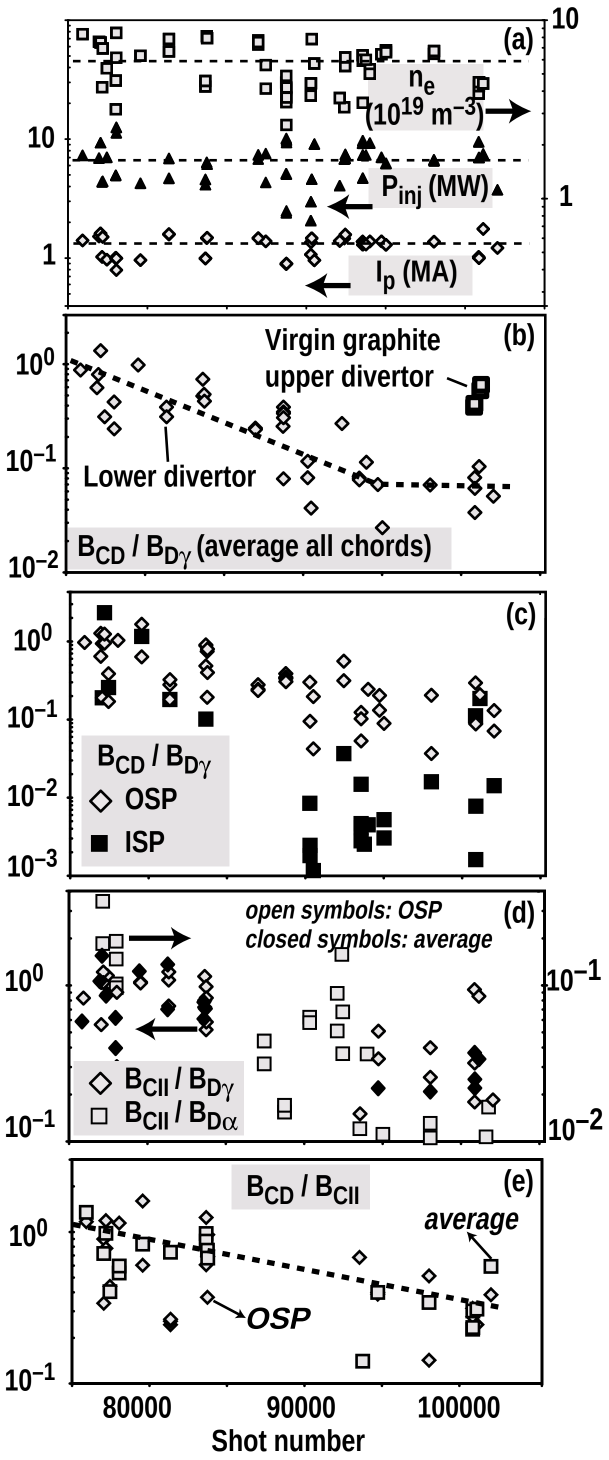

Fig. 1. Spectroscopy of divertor carbon erosion in DIII–D from 1992 (#75000) to 2000 (#100100). ELMy H–mode confinement regime with attached outer divertor plasma unless otherwise noted. Definitions: $B_{CD}/B_{D\gamma} \propto Y_{chem}$, $B_{CII}/B_D \propto Y_{C;total}$, $B_{CD}/B_{CII} \propto$ relative contribution of chemical erosion, OSP: outer strikepoint region, ISP: inner strikepoint region, average: average ratio from all divertor chords.

A spectroscopic survey of divertor hydrocarbon molecular emissions shows that the typical chemical erosion yield has decreased significantly over the last eight years [Fig. 1(b)]. Average $B_{CD}/B_{D\gamma}$ ratio has decreased a factor of 10–20 since 1992. Spatial discrimination of the data indicates reductions at both strikepoint regions, with a larger decrease occurring at the inner strikepoint (ISP) [Fig. 1(c)]. Virgin graphite tiles were installed as part of the newly designed DIII–D upper divertor in late 1999. As expected, the subsequently measured $B_{CD}/B_{D\gamma}$ ratio from the upper divertor is consistent with those measured for virgin graphite.

A direct comparison of $B_{CD}/B_{D\gamma}$ from nearly identical core and divertor plasmas in 1993 and 1999 clearly illustrates the large change in divertor chemical erosion across the lower divertor (Fig. 2 and Table 2). This comparison further ensures that the long-term changes found in the survey are not due to a systematic trend in the discharges.

The total flux of carbon ions entering the divertor plasma has decreased significantly since 1992, in conjunction with the relative decrease in chemical erosion [Fig. 1(d)]. As with chemical erosion this is confirmed by a comparison of nearly identical plasmas [Fig. 2(b)]. The ratio of B_{CII}/B_D reveals that the carbon source rate has decreased on average a factor of three near the OSP.

2.5. CORE PLASMA CARBON

Despite the apparently changing lower divertor carbon source, no significant decrease in the core plasma carbon fraction, f_C, has occurred since 1992 [Fig. 3(b)]. This survey uses the same set of ELMy H–mode attached discharges as used in chemical erosion study of 2.4. Also shown is average f_C for ELMy H–mode plasmas from a ~2000 shot database implemented in 1999 (large square in [Fig. 3(b)]). On average f_C ~3% is found, but with significant scatter. An additional database of f_C values from standard lower divertor L–mode plasmas (used for L-H transition studies) shows small changes in f_C from 1993 to 1999.

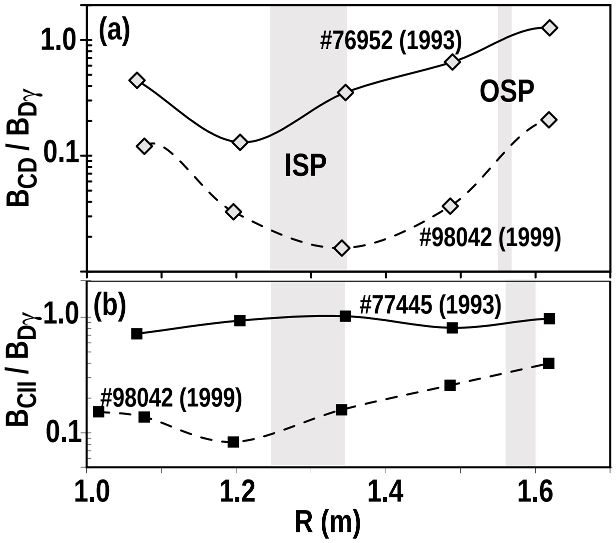

Fig. 2. Direct comparison of nearly identical plasma shots with virgin (1993) and conditioned (1999) graphite tiles in DIII–D. Core and divertor plasma parameters in Table 2, (a) Relative chemical yield from $B_{CD}/B_{D\gamma}$, (b) Relative total carbon yield based on $B_{CII}/B_{D\gamma}$.

Table 2
Core and outer divertor parameters for direct comparison of carbon yield (Fig. 2)

Shot	Date	I_p (MA)	n_e (10^{19} m^{-3})	P_{inj} (MW)	$\Gamma_{i,OSP}$ (s^{-1}m^{-2})	$T_{e,OSP}$ (eV)
76952	03-93	1.5	7.6	6.9	2.5×10^{22}	25
77445	05-93	1	5.7	7.2	1.8×10^{22}	35
98042	01-99	1.4	6.8	6.6	3×10^{22}	26

With regard to other source locations, based on SPRED UV spectroscopy, no significant decrease has occurred in the relative carbon erosion rate at the outer midplane [Fig. 3(a)] in ELMy H–mode. In a similar fashion to B_{CII}/B_D in the divertor, this is based on the ratio of CIII resonance transition (977 Å) to deuterium Lyman-β (1025 Å). The L–mode data-set described above shows at most factor of two to three decrease in $B_{CIII}/B_{D\text{-}Ly\beta}$ since 1993.

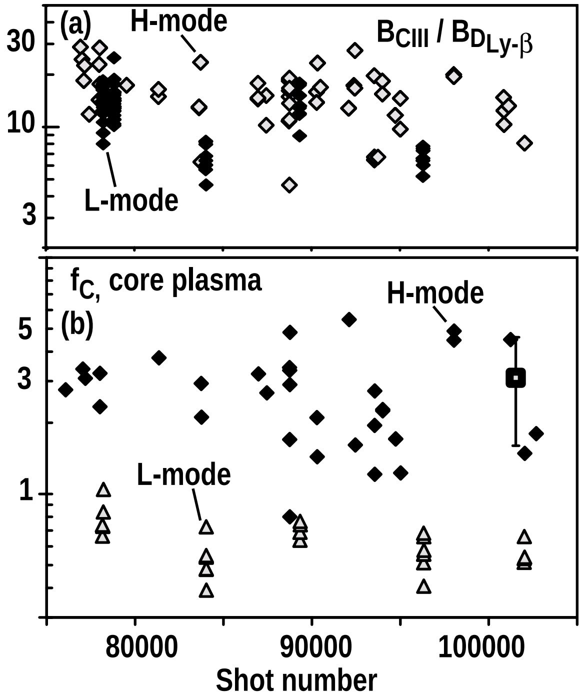

Fig. 3. Survey of core plasma for ELMy H–mode shots of spectroscopy survey and for standard L–mode discharges: (a) Midplane VUV relative carbon emission (b) Core carbon fraction in %.

3. DISCUSSION

3.1. INTERPRETATION OF DIVERTOR YIELDS

Conversion of the relative emission strengths (Section 2.4) into yield allows one to estimate the magnitude and relative importance of chemical erosion in the DIII–D lower divertor since 1993. For the reasons outlined in Section 2.3, we restrict this analysis to regions near the OSP. Interpretation of ISP data is made difficult by the uncertain level of plasma detachment there, especially considering the large sensitivity of D_γ to the presence of volume recombination [16]. However, even with restriction of analysis to the OSP region, one must not regard such a simple exercise based on a spectroscopy survey as a serious attempt at extract absolute yield measurements. The significant scatter in emission ratio data witnesses the uncontrolled nature of the incident plasmas and exposure conditions. Nevertheless, this remains an important exercise both in understanding the overall trends seen in the emission ratios and in assessing the validity of the large relative changes seen over time.

The chemical erosion yield [Eq. (1)] of DIII–D virgin graphite tiles is Y_{chem} ~2.5%–5% (for $B_{CD}/B_{D\gamma} = 1$, $(D/XB)_{CD_4}$ from Table 1) for exposure to attached ELMy H–mode plasmas (T_e~20, incident ion energy ~ 3–5 T_e~60–100 eV). This yield is in reasonable agreement with the expected yield based on laboratory ion-beam measurements [5] with typical OSP tile temperature ~500 K. Other tokamaks also report a similar yield when using a similar spectroscopic technique [13,17]. This strongly suggests that *in-situ* conditioning has indeed reduced the expected Y_{chem} from expected values of virgin graphite, based on the large relative decrease in B_{CD}/B_D.

Total equivalent ionic carbon yield [Eq. (2)] in 1993 was $Y_{C,total}$ ~2%–3% from typical $B_{CII}/B_{D\gamma}=1$ and $Y_{C,total}$ ~ 5%–10% from $B_{CII}/B_{D\alpha} = 0.2$. Therefore the “effective yields” of chemical and total erosion were of similar magnitude in 1993 (allowing for the simplistic nature of this analysis and the significant scatter in the data). Importantly, the approximately three-fold reduction in $Y_{C,total}$, 1993 to 1999, is not inconsistent with the expected minimum achievable yield from carbon physical sputtering by deuterium ions (~ 2% for T_e=20 eV, incident angle ~50° [18]), which has presumably remained constant.

It is noted that similar results in yield calculations are obtained from the side-by-side comparison (Fig. 2) of nearly identical discharges between 1993 and 1998–99. Since these plasmas are known to possess very similar plasma conditions at the OSP, this result lends further confidence to the simple analysis of the spectroscopy survey.

An additional comparison of simultaneously measured B_{CD}/B_{CII} shows that the relative importance of chemical erosion as a source of carbon has been reduced [Fig. 1(e)]. One can estimate the relative contribution of molecules to carbon ion source into the divertor using $f_{chem} = (B_{CD}/B_{CII})\cdot(D/XB)_{C^+}/(S/XB)_{CII,4268\ \text{Å}}$. It is found from 1993 that f_{chem} ~ 30% –50% near the outer strikepoint, with f_{chem} being reduced on average a factor of 3–5 by 1999.

The cause of the reduced chemical erosion yield is under investigation; but is assumed to be an effect of either plasma or boronization conditioning. Current investigations are focussing on the role of boron [19], which as a dopant is known to reduce carbon chemical erosion yield. These investigations will be reported in a future article.

3.2. CORE CARBON CONTAMINATION

Two possible explanations are being explored concerning the essentially constant core carbon concentration with decreasing divertor source. Both explanations have supporting evidence but are not proven.

The first explanation is that the divertor is not the main source location of impurities found in the core plasma, i.e. the main chamber wall is relatively more important as an impurity source. This hypothesis is qualitatively supported by the weakly changing mid-plane carbon source rate since 1992 (Fig. 3). The relatively poor diagnosis of plasma-material interactions at the main wall, and likely poloidal and toroidal non-uniformity, hamper such investigations.

The second explanation being examined is that plasma impurity transport adjusts such that core contamination varies non-linearly with the source rate of impurity at the plasma-wall interface. Such a result has recently been found in modeling using the UEDGE multi-fluid code [20]. Both divertor screening and the far-edge plasma flow pattern adjust in small ways that affect carbon transport to the core. Unfortunately, direct testing of such a modeling result is quite difficult.

4. CONCLUSION

A spectroscopic survey of carbon chemical and total erosion has been performed for the DIII–D lower divertor since the installation of virgin graphite tiles in 1992. The principal result of the spectroscopy survey is that the erosion rate of carbon from the lower divertor graphite tiles has gradually evolved over the eight years since their installation in 1992. Based on the spectroscopy survey, newly installed graphite tiles exhibit chemical erosion consistent with results from laboratories and other tokamaks. In contrast, recent discharges on conditioned tiles show relatively weaker chemical erosion, as well a reduced emission from singly ionized carbon, indicating a reduction in the total source rate of carbon due to sputtering. Despite the relative reduction in carbon source rate from the lower divertor, the survey finds no significant reduction in the core carbon concentration.

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