DiMES studies of temperature dependence of carbon erosion and re-deposition in the lower divertor of DIII-D under detachment

D.L. Rudakov,[a] W. Jacob,[b] K. Krieger,[b] A. Litnovsky,[c] V. Philipps,[c] W.P. West,[d] C.P.C. Wong,[d] S.L. Allen,[e] R.J. Bastasz,[f] J.A. Boedo,[a] N.H. Brooks,[d] R.L. Boivin,[d] G. De Temmerman,[g] M.E. Fenstermacher,[e] M. Groth,[e] E.M. Hollmann,[a] C.J. Lasnier,[e] A.G. McLean,[h] R.A. Moyer,[a] P.C. Stangeby,[h] W.R. Wampler,[i] J.G. Watkins,[i] P. Wienhold,[c] J. Whaley[f]

[a]*University of California, San Diego, La Jolla, California 92093-0417, USA*
[b]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany*
[c]*Institut für Plasmaphysik, Forschungszentrum Jülich, Association EURATOM-FZJ, 52425 Germany*
[d]*General Atomics, San Diego, California 92186-5608, USA*
[e]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[f]*Sandia National Laboratories, Livermore, California, USA*
[g]*Institute of Physics, University of Basel, Klingelbergstrasse 82, CH-4056, Basel, Switzerland*
[h]*University of Toronto Institute for Aerospace Studies, Toronto, Ontario, Canada M3H 5T6*
[i]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*

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Abstract

A strong effect of a moderately elevated surface temperature on net carbon deposition and deuterium co-deposition in the DIII-D divertor was observed under detached conditions. A graphite DiMES sample with a 2 mm wide, 18 mm deep gap lined with silicon catcher plates was exposed to lower-single-null (LSN) L-mode plasmas first at room temperature, and then pre-heated to 200°C by a built-in electrical heater. At the elevated temperature, deuterium co-deposition in the gap was reduced by an order of magnitude. At the plasma-facing surface of the pre-heated sample net carbon erosion was measured at a rate of 3 nm/s, whereas without pre-heating net deposition is normally observed under detachment. In a related experiment three sets of molybdenum mirrors recessed 2 cm below the divertor floor were exposed to identical LSN ELMy H-mode discharges. The first set of mirrors exposed at ambient temperature exhibited net carbon deposition at a rate of up to 3.7 nm/s and suffered a significant drop in reflectivity. In contrast, two other mirror sets exposed at elevated temperatures between 90°C and 175ºC exhibited practically no carbon deposition and their optical reflectivity in the wavelength range above 500 nm was essentially preserved.

I. INTRODUCTION

The Divertor Material Evaluation System (DiMES) [1] at the DIII-D tokamak [2] is aimed at studies of plasma-material interactions in a tokamak divertor. Since DIII-D has plasma-facing components (PFCs) made of carbon, studies of carbon erosion, migration and re-deposition constitute the focus of the DiMES research program [3].

The current design of the ITER divertor incorporates carbon-fiber-composite (CFC) tiles at the divertor targets [4]. Carbon will be eroded from the targets by physical and chemical sputtering, and then re-deposited on the PFCs [5]. This process may lead to a number of potential problems for plasma operations, in particular tritium accumulation due to co-deposition with carbon on the faces of PFCs and in gaps between them, as well as in other remote areas such as structures under the divertor dome and pump duct entrances. Deterioration of diagnostic mirrors caused by carbon deposition is also a strong concern [6].

Carbon deposition and tritium co-deposition can be mitigated by re-erosion. A complete description of chemical erosion of carbon by hydrogenic ions has been developed [7]. However, most of the gaps between PFCs and other remote areas are not accessible to ions, so re-erosion by atomic hydrogen is of more relevance for those regions. Laboratory experiments have shown that the chemical erosion rate of graphite and amorphous hydrocarbon (a-C:H) films by atomic H and D peaks at 300-400°C, where it is about an order of magnitude higher than at room temperature [8,9]. An exponential increase of the re-erosion rates of plasma-deposited a–C:H layers with increasing substrate temperature has been observed in low-temperature methane plasmas [10,11]. Although pure methane was used as working gas in these experiments, a transition from net deposition at ambient temperature to net erosion at elevated temperature was observed. The transition temperature depends on experimental conditions, such as ion energy and particle fluxes to the surface. It was between 200 and 300°C in these experiments [10]. Similar results, i.e. a transition from net deposition to net erosion, were found in the PSI-2 plasma generator [12]. Under these experimental conditions, the transition temperature was about 100°C. Recent analysis of long term samples mounted in ASDEX Upgrade underneath the divertor dome baffle showed that the growth rate of hydrocarbon layers on these samples decreased strongly with increasing sample temperature [13]. The deposition of both D and C at 200°C was about 70 times smaller than at room temperature.

PFC temperature in ITER will be significantly higher than in most present day devices. The cooling water temperature setting the lower temperature limit of the PFCs will be 100-150°C [4], while the plasma-facing surfaces are likely to get much hotter. There is a hope that increased surface temperature of the PFCs in ITER may mitigate carbon re-deposition and tritium co-deposition [14]. Experiments under ITER-relevant conditions are urgently needed to improve projections of the tritium retention in ITER. A few recent DiMES experiments performed in the lower divertor of DIII-D tokamak to study the temperature dependence of the carbon erosion/re-deposition are reviewed in this article. The experiments were performed under detached divertor conditions, where the divertor tile surface temperatures were between 30-60°C. Pre-heating of DiMES samples using internal electrical heaters was used to attain the lower range of ITER-relevant surface temperatures.

II. STUDIES OF CARBON DEPOSITION AND DEUTERIUM CO-DEPOSITION DOWN TILE GAPS

Uncontrolled increase of tritium inventory due to co-deposition with carbon is a critical challenge for ITER [5]. A large fraction of the retained tritium may be accumulated in gaps between PFCs and other remote areas that are not accessible for most proposed tritium removal techniques. A series of dedicated experiments was performed in DIII-D to measure carbon deposition and deuterium co-deposition (as a proxy for tritium) in a simulated tile gap and an attempt to mitigate the deposition by enhanced chemical re-erosion at elevated surface temperature was made.

A graphite DiMES sample head with a simulated tile gap 2 mm wide, 15 mm long and 18 mm deep has been fabricated. The inside of the gap was lined with silicon catcher plates to optimize the resolution of the deposition thickness measurements. The sample featured a built-in heater and a thermocouple for in-situ temperature control.

In order to quantify the mitigation of the net carbon deposition and deuterium co-deposition by enhanced chemical re-erosion at elevated surface temperature, two exposures of the tile gap sample were performed, first at room temperature (~30°C) and second at 200°C. In both experiments the samples were exposed to nine reproducible ohmic lower single-null (LSN) discharges in deuterium with the outer strike point (OSP) kept at the DiMES radial location for most of the discharge. The discharge parameters were: toroidal magnetic field, B_T = 2 T, plasma current, I_p = 1.1 MA, ohmic heating power, P_{ohm} ~ 1 MW. The line average density was at $4.5\text{x}10^{13}$ cm^{-3} for about 3 s, and the OSP was detached most of the time. Electron temperature and density measured by divertor Thomson scattering [15] near the OSP were T_e = 0.6-1.2 eV and n_e = $1\text{-}2\times10^{20}$ m^{-3}. The incident ion flux measured by a floor Langmuir probe at the radial location of the sample was about 2×10^{21} $m^{-2}s^{-1}$. The total exposure time in both cases was about 30 s. In each case, the sample was inserted so that its plasma-facing surface was leveled with the divertor floor and the gap was oriented radially. The angle between the magnetic field direction and the sample surface was about 1.3 degrees, so charged particles could not reach inside the gap and any erosion/deposition on the catcher plates must be due to neutrals. Unfortunately, no measurements of the neutral pressure/flux were available at the sample location.

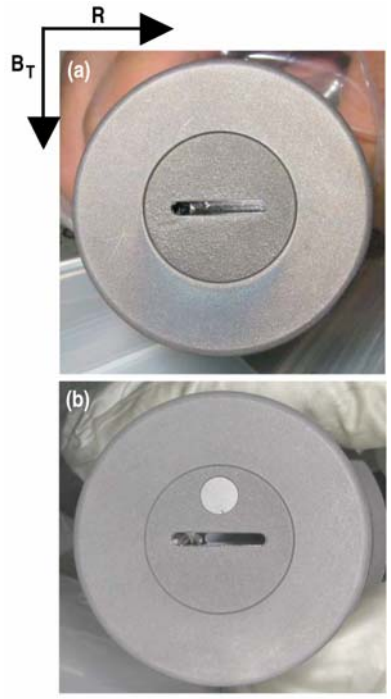

Fig. 1. Plasma-facing surface of the tile-gap sample after plasma exposure at ambient temperature (a) and pre-heated to 200°C (b).

Photographs of the plasma-facing surface of the gap sample after each plasma exposure are shown in Fig. 1. After each exposure, the silicon catcher plates were removed from the gap and the deposits were analyzed by ellipsometry and ion beam analysis (IBA). Both ellipsometry and IBA analyses of the catcher plates from the non-heated exposure showed measurable amounts of deposited carbon on all plates. The deposit thickness on the side plates decreased exponentially with the distance from the plasma-facing side of the gap, with a decay

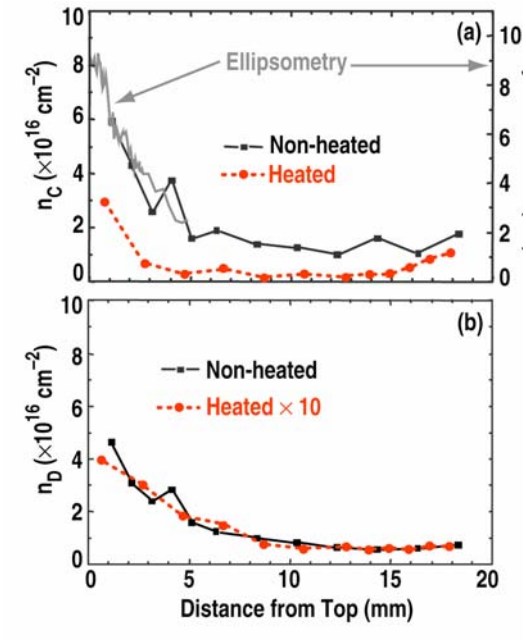

Fig. 2. Profiles of the carbon (a) and deuterium (b) areal density measured by IBA versus the distance from the gap entrance for the ambient temperature (squares) and pre-heated (circles) exposures. The thickness profile measured by ellipsometry for the non-heated case (gray line in (a), scale on the right) compares well with IBA data.

length of about 1–3 mm [Fig 2(a)]. The deposit thickness profiles from ellipsometry were in good agreement with the carbon number density from IBA. The deposited layer was of the soft amorphous type with D:C atomic ratio of 0.4–0.7, as measured by IBA.

Figure 2 shows measured profiles of the carbon (a) and deuterium (b) number density versus the distance from the gap entrance for the non-heated and heated exposures. Carbon deposition in the heated gap was lower by a factor of 3-4, and the amount of co-deposited deuterium was reduced by about an order of magnitude in the heated exposure [note the different scale in Fig. 2(b)]. This is a very encouraging result for ITER, suggesting that moderately elevated temperature can significantly reduce tritium accumulation in tile gaps. Ellipsometry failed to resolve the thickness of the deposited layer which appeared rather hard. More details on the results of the catcher plate analyses are available in Ref. [16].

III. EFFECT OF ELEVATED SURFACE TEMPERATURE ON CARBON EROSION FROM A PLASMA-FACING SURFACE

No measurements of the net erosion/deposition rate at the plasma-facing surface of the sample were available for the non-heated gap sample exposure. However, the colored area seen in figure 1(a) is a strong indication of an a-C:H film deposited on the surface. This is in agreement with earlier studies [17] which show net deposition under detached divertor conditions. For the heated exposure a depth-marked graphite button was installed on the plasma-facing surface of the sample [Fig. 1(b)]. After the exposure the button was analyzed by IBA. Total net erosion of 90 ± 4 nm, corresponding to an average rate of about 3 nm/s, was measured at five different locations on the button. This is a rather high erosion rate (in reactor terms equal to about 9 cm per burn-year), comparable to the highest erosion rates observed in DIII-D divertor under attached high-power H-mode conditions [17]. The most reasonable explanation for such a high erosion rate observed under detachment is enhancement of chemical erosion by the elevated surface temperature, in line with observations of Refs. [7-13]. To test this hypothesis, we exposed another depth marked DiMES sample maintained at ambient temperature to a series of seven L-mode discharges with detached OSP and plasma parameters close to those of the tile-gap-exposure discharges. In this experiment the OSP was swept across the divertor floor radially inward, so that during each discharge DiMES spent about 2 s in the private flux zone (PFZ), then about 1 s near the OSP, and finally about 0.5 s in the scrape-off-layer (SOL) just outside the OSP. The total exposure times at the PFZ, OSP and SOL were about 14, 7 and 3.5 s, respectively. The incident ion flux in the SOL was comparable to that near the OSP, while in the PFZ it was an

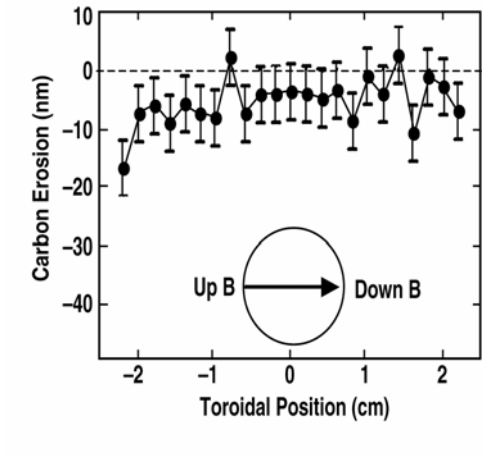

Fig. 3. Profile of the net carbon erosion across a non-heated DiMES sample exposed to seven detached LSN L-mode discharges with OSP sweeps. Negative erosion corresponds to net deposition.

order of magnitude lower. Therefore, total exposure time at a region with comparatively high ion flux was about 10 s. The resulting net erosion/deposition was too low to be definitively resolved by IBA, though within the error bars for the measurement the data were biased towards net deposition [Fig. 3]. The high net erosion rate observed in the heated experiment was definitely not reproduced. Therefore, the erosion must have been caused by the elevated surface temperature.

IV. MITIGATION OF CARBON DEPOSITION ON DIAGNOSTIC MIRRORS AT ELEVATED SURFACE TEMPERATURE

Optical diagnostics in ITER will rely on plasma-facing mirrors to view the plasma [6]. The mirrors will be used over a wide wavelength range and will be required to maintain good optical performance over full lifetime of ITER. They may suffer from erosion by energetic plasma particles and charge exchange atoms and deposition of surface contaminants, the latter being of particular concern in the divertor region where the neutral densities are high [6].

First dedicated tests of ITER-candidate molybdenum mirrors were recently performed in the lower divertor of DIII-D using DiMES [18,19]. Three experiments were performed. In each experiment two mirrors were installed on a specially designed stainless steel holder that was inserted in the divertor floor, as shown in Fig. 4. The two mirrors faced opposite toroidal directions, their centers were about 2 cm below the floor. The mirrors were exposed to highly reproducible H-mode LSN discharges in deuterium with the following discharge parameters: B_T = 2 T, I_p = 1.1 MA, neutral beam heating power, P_{NBI} = 6.6 MW, average plasma density, $\overline{n}_e$ = 8×10^{19} m^{-3}. During the exposure the mirrors were located in the PFZ. The divertor was detached and electron temperature and density measured by divertor Thomson scattering [15] in the PFZ near the floor were T_e = 0.5-2 eV and n_e = 2-5$\times10^{20}$ m^{-3}. The deuteron flow

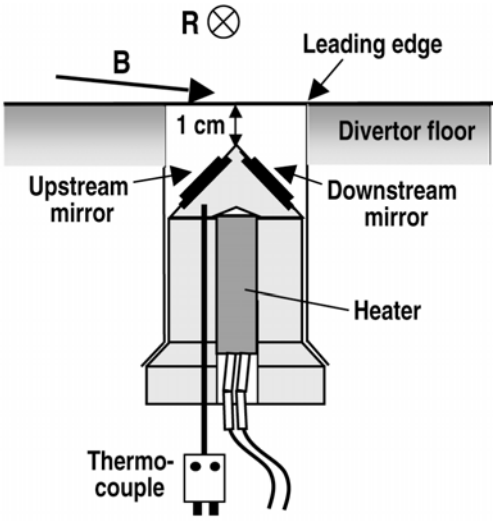

Fig. 4. Geometry of the mirror exposure experiment in the DIII-D divertor.

to the divertor floor was in the direction of B shown schematically in Fig. 4 (as confirmed by Mach probe measurements); hence the designations "upstream" and "downstream". The angle between the magnetic field direction and the divertor floor surface was less than 1 degree, so the mirrors were not accessible to charged particles. Measurements of the neutral flux incident on the mirrors were not available. A rough estimate made from the pressure measurements below the divertor floor in the PFZ of comparable discharges gave a neutral flux of about 1×10^{22} $m^{-2}s^{-1}$.

Two sets of mirrors were exposed on two consecutive days. The first set was exposed to six plasma discharges for a total time of about 25 s. No active temperature control was used, but the holder and the mirrors were heated by the plasma radiation and charge exchange atom fluxes. At the beginning of the exposure the holder temperature was 23°C, by the end of the 6th exposure discharge it was at about 44°C.

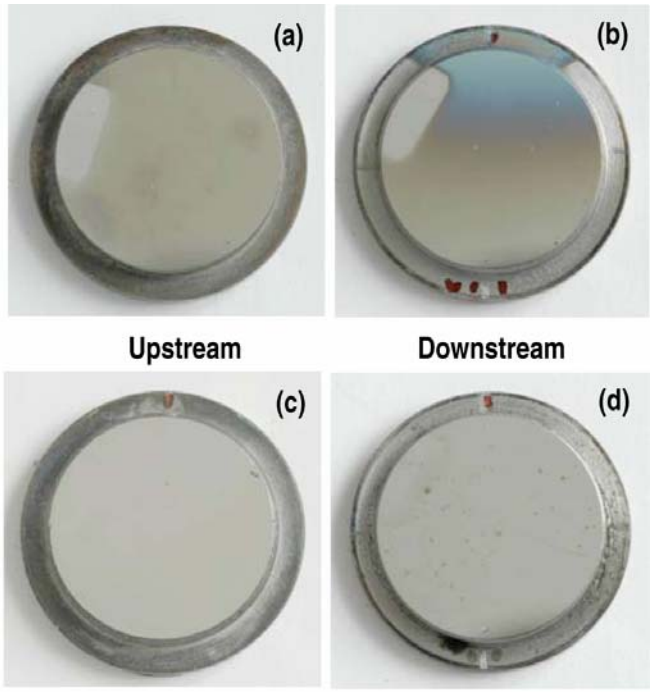

Fig. 5. Photographs of mirrors exposed at ambient (a) and (b), and elevated (c) and (d) temperature.

Upon removal from the vacuum chamber, visible deposits were found on both mirrors [Figs. 5(a) and 5(b)]. A strong asymmetry was seen in the deposition between the upstream and downstream mirrors. The deposition on the upstream mirror was rather uniform, while on the downstream mirror a clear gradient was observed, with the heaviest deposits found near the top of the mirror. This was probably caused by re-deposition of the carbon sputtered locally from the leading edge of the downstream graphite tile. The areal carbon coverage, measured by secondary ion mass spectroscopy (SIMS) and IBA, was comparable in the centers of the upstream and downstream mirrors, while at the top of the downstream mirror it was about a factor of 2 higher. The thickness of the deposited hydrocarbon film was largest near the top of the downstream mirror; its value of 93 nm measured by spectroscopic ellipsometry corresponds to a net deposition rate of 3.7 nm/s. The net deposition rate near the centers of both mirrors was about 2 nm/s. The deposited film was of the soft type with D:C ratio of about 0.5, as measured by IBA. The deposits caused the mirror reflectivity in the wavelength range between 250-1000 nm to degrade by 15-70% [Fig. 6].

In order to mitigate the carbon deposition by chemical re-erosion, the mirrors were pre-heated using the internal heater prior to the second exposure. A failure of the heater before the experiment caused the holder and the mirrors to slowly cool down under vacuum during the exposure. The holder temperature at the beginning of the experiment was at 140°C, decreasing to about 90°C by its end. The mirrors were exposed to 17 plasma discharges, for a total time of about 70 s.

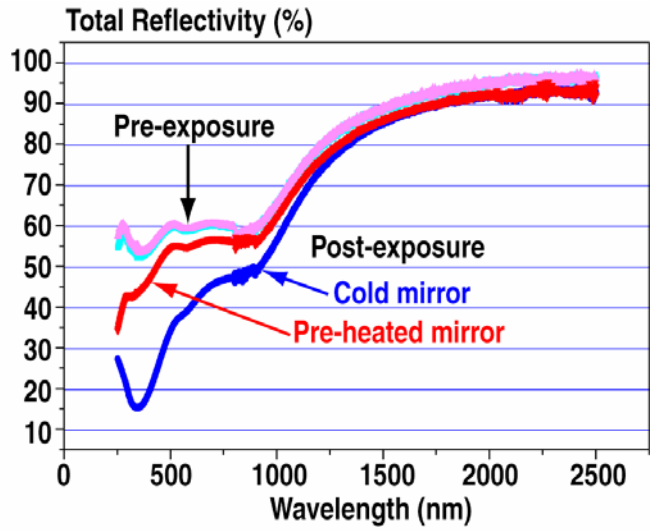

Fig. 6. Total reflectivity of the downstream mirrors before and after exposures at ambient temperature and with active pre-heating.

When the mirrors were removed from DiMES, no deposits were visible on either of them [Figs. 5(c) and 5(d)]. Low carbon content on the heated mirror surfaces was confirmed by SIMS and IBA analyses. The areal carbon density on the heated mirrors from IBA was a factor of 10-30 lower than on the non-heated ones. Since the total exposure time of the heated mirrors was almost three times longer compared to non-heated ones, this corresponds to the net carbon deposition rate being lower by a factor of 30-100. The reflectivity of the heated mirrors was essentially preserved in the wavelength range above 500 nm, while below 500 nm a decrease in the reflectivity was observed [Fig. 6]. X-ray photoelectron spectroscopy measurements showed that this decrease was due to surface oxidation, caused presumably by the long term storage in air.

We should note that by the end of each plasma discharge the mirrors could be at a higher temperature than the bulk temperature of the holder, as measured by the thermocouple. More recently another mirror exposure with better temperature measurement and control has been performed. In this experiment the temperature was measured directly at the back of one of the mirrors and maintained at 150±7°C prior to each plasma discharge. The mirrors were exposed to 8 plasma discharges for a total of about 36 s. The main discharge parameters were similar to those of the previous experiments but the divertor density was about twice lower (see Table 1). The increase of the mirror temperature after each discharge was about 15°C. No visible deposition was observed on either of the mirrors after the exposure. Therefore, mitigation of carbon deposition on the mirrors by moderately increased temperature was confirmed. Preliminary analysis showed that the reflectivity of the mirrors was essentially preserved throughout the wavelength range of 250-2500 nm. Detailed analysis of the mirrors is forthcoming.

V. DISCUSSION AND SUMMARY

Plasma conditions in ITER divertor are expected to vary over a very wide range depending on the exact location [5]. For example, B2-EIRENE modeling of a reference semi-detached edge plasma gives the following range of the plasma parameters along the CFC portion of the divertor targets [5]: T_e = 1-15 eV, $n_e = 1\times10^{19}$-2×10^{21} m^{-3}, ion flux 2×10^{21}-1×10^{24}m^{-2}s^{-1}, neutral flux 5×10^{20}-2×10^{24}m^{-2}s^{-1}. It is impossible to fully reproduce this range of conditions in any of the existing machines. Still, experiments performed under much narrower range of conditions falling within the wider ranges above can be very useful to benchmark modeling and improve its predictive capability.

Table 1. Summary of the experiments.

Experiment	Discharge type	Sample location[a]	T (°C)[b]	Exposure time (s)	$n_e \times 10^{20}$ (m^{-3})[c]	T_e (eV)[c]	Deposition rate (nm/s)[d]
Tile gap	L-mode	OSP	~30	30	1-2	0.6-1.2	0.3
Tile gap	L-mode	OSP	200	30	1-2	0.6-1.2	0.1
Surface erosion	L-mode	OSP	200	30	1-2	0.6-1.2	-3
Surface erosion	L-mode	OSP+SOL	~30	~10	1-2.5	0.8-1.6	0
Mirrors	H-mode	PFZ	23-44	25	2-5	0.5-2	2-3.7
Mirrors	H-mode	PFZ	90-140	70	2-5	0.5-2	<0.1
Mirrors	H-mode	PFZ	150±7	36	1-2	0.5-2	0

[a] OSP = Outer Strike Point, PFZ = Private Flux Zone, SOL = Scrape-Off Layer

[b] Pre-discharge bulk sample temperature

[c] Divertor plasma parameters measured by Thomson scattering at the sample radial location

[d] Maximum absolute value quoted. Negative deposition corresponds to net erosion. "0" means net erosion/deposition was below the measurement resolution.

In a number of recent experiments performed in the lower divertor of DIII-D under ITER-relevant plasma conditions (see Table 1), a moderately elevated surface temperature has been observed to significantly influence carbon erosion/re-deposition and deuterium co-deposition rates. The effect may be qualitatively explained by increased chemical erosion rates by neutrals and ions at elevated temperatures [7-13]. The effect is observed on both plasma-facing surfaces and surfaces not accessible to charged particles and appears to affect bulk carbon as well as plasma-deposited a-C:H films. The observed reduction of carbon deposition and hydrogenic co-deposition down tile gaps at elevated temperature is potentially good news for ITER. However, if the carbon erosion rates from the plasma-facing surfaces are also increased at higher temperatures, increased carbon impurity production may offset the advantage of higher re-erosion rates in the gaps. On the other hand, temperature control offers an attractive means of mitigating carbon deposition on small individual objects, such as diagnostic mirrors, that can be allowed to heat up (or be actively heated) to moderately high temperatures without negative consequences.

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