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Control of High-Z PFC Erosion by Local Gas Injection in DIII-D*

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Abstract

Reduced erosion of a high-Z PFC divertor surface was observed in DIII-D with local injection of methane and deuterium gases. Molybdenum-coated silicon samples were exposed in the lower divertor of DIII-D using DiMES under plasma conditions previously shown to cause significant net erosion of Mo. Three exposures with $^{13}CH_4$ and one exposure with D_2 gas injection about 12 cm upstream of the samples located within 1–2 cm of the attached strike point were performed. Reduction of Mo erosion was evidenced *in-situ* by the suppression of MoI line radiation at 390.2 nm once the gas injection started. Post-mortem ion beam analysis demonstrated that the net erosion of molybdenum near the center of the samples exposed with

$^{13}CH_4$ injection was below the measurement resolution of 0.5 nm, corresponding to a rate of ≤0.07 nm/s. Compared to the previously measured erosion rates, this constitutes a reduction of more than 6–10X.

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1. Introduction

High-Z materials such as tungsten will be used for plasma facing components (PFCs) in the divertor of ITER [1] and very likely in devices beyond ITER. PFC erosion will produce high-Z impurities that may lead to unacceptably high radiation losses if they enter the plasma core. It is envisaged that erosion of the main divertor plates will be controlled by detachment [2] induced by injection of radiating gas. However, this may leave some critical PFCs such as divertor baffles, startup/protection limiters, etc., vulnerable to excessive erosion and surface damage including melting, particularly during transients such as Edge Localized Modes (ELMs) and disruptions. A sacrificial low-Z coating deposited on a high-Z PFC surface can protect the surface from erosion and damage. However, a thin coating will quickly erode, so it has to be renewable in-situ. Injection of a gas containing low-Z impurities such as B, C, Si, or Li through capillaries at a PFC surface can lead to the local deposition of a low-Z coating on the surface due to a local decrease of the electron temperature (T_e) and increase of the low-Z impurity content (see Section 2). Previous work in TEXTOR [3] demonstrated the effectiveness of *in-situ* coatings produced by the local injection of silane gas (SiH_4) for controlling erosion of the leading edge of a graphite limiter. In the experiments reported here, we suppressed erosion of molybdenum (Mo) by using methane gas injection upstream of Mo-coated samples in the DIII-D divertor.

While creating a protective low-Z coating *in-situ* is an attractive concept, it has certain disadvantages: eroded low-Z impurities would re-deposit elsewhere, potentially leading to tritium retention and accumulation of dust and debris from exfoliating re-deposited layers. In case of carbon, this problem may potentially be alleviated by thermal oxidation [4]. However, this solution is unlikely to be acceptable for ITER. Therefore, we also tested the reduction of Mo erosion by the local injection of non-depositing D_2 gas. This technique, while probably less effective for PFC protection from transients, may possibly be used for alleviating erosion

of PFCs where critical heat loads may exist for relatively short and given periods of time, e.g. ITER startup limiters.

2. Background: balance between erosion and deposition

It can be shown from first-principle considerations that local injection of a gas containing low-Z impurity can shift the balance between erosion and deposition of the impurity from net erosion to net deposition. For example, with carbon impurity in deuterium plasma, the balance depends on the ratio of the C and D fluxes to the surface, $f_C = \Gamma_C / \Gamma_D$, the local electron temperature (T_e) and the surface temperature [5]. For given f_C and surface temperature, one can calculate $T_{e,th}(f_C)$, the threshold T_e at which the thickness of the carbon layer neither increases nor decreases.

Figure 1 shows the calculated dependence of $T_{e,th}(f_C)$ (for details of the calculation see[5]). The regions to the right of the curves correspond to net erosion and the regions to the left correspond to net deposition. Thus, for a given surface temperature, the transition from net erosion to net deposition of carbon can be achieved by either increasing f_C or decreasing T_e. Injection of a gas containing C (e.g. methane) is likely to cause both of those effects, thus, when performed near a high-Z PFC surface, it may reduce the surface erosion via creating a protective coating. Injection of a gas not containing carbon (e.g. D_2) is likely to locally decrease both f_C (through dilution) and T_e, thus its effect is harder to predict.

3. Experimental approach

Exposures of Mo-coated samples were conducted in the lower divertor of the DIII-D tokamak [6]. In order for net erosion to be measurable by ion beam analysis (IBA), 15-75 nm thick Mo films deposited on 1 cm diameter silicon disks were used. The samples pre-characterized by IBA were installed in graphite casings and inserted in the lower divertor of DIII-D using the Divertor Material Evaluation System (DiMES) manipulator [7]. For the first

two exposures, the Mo-coated samples were mounted in the center of the DiMES head ~5 cm in diameter [Fig. 4(a,b)]. For the latest two exposures, a DiMES head featuring an embedded Langmuir probe (LP) downstream of the samples was employed [Fig. 4(c)]. The LP allowed measurements of the local plasma density (n_e) and T_e before and during the gas injection. MoI emission near the samples was monitored by an absolutely calibrated digital CMOS camera and a high resolution MDS spectrometer [8].

All experiments were performed in deuterium discharges, in a lower single null (LSN) magnetic configuration. Location of DiMES and arrangement of the optical diagnostics are shown in Fig. 2(a). The outer strike point (OSP) was moved to the inboard edge of the DiMES samples once stable plasma conditions were achieved and dwelled there for 3-4 s in each exposure discharge. Gas was injected through a capillary opening through a hole in a floor tile ~12 cm upstream from the center of the DiMES head [Fig 2(b)].

Net erosion of Mo and deposition of carbon were measured by post-mortem IBA [9]. Mo erosion was measured by Rutherford backscattering spectroscopy (RBS) with 2 MeV ^{4}He; C and D deposition were measured by nuclear reaction analysis (NRA) with 2.5 MeV ^{3}He. In order to discriminate between the carbon originating from the gas injection and that from the background plasma, stable, isotopically enriched $^{13}CH_4$ methane (99% ^{13}C) was used for the injection.

4. Experimental results

Four samples were exposed in two experiments. In the first experiment both exposures were with a $^{13}CH_4$ gas injection, first in four L-mode discharges for ~14 s total exposure time (exposure #1), and second in two H-mode discharges for a total of ~7 s (exposure #2). In the first two L-mode exposure discharges gas injection started at 2.5 s, 1.5 seconds after the OSP was moved to the sample. In the last two L-mode discharges and in both H-mode discharges,

gas injection started at 1.0 s, concurrently with the OSP move. Figure 3(a) shows temporal evolution of the MoI signal at 390.2 nm measured by the MDS spectrometer with $^{13}CH_4$ gas injection at a rate of 0.5 Torr-l/s in L-mode. At that injection rate the measured emission was reduced by about a factor of 3. In subsequent discharges with a gas injection rate of 1.5 Torr-l/s, the MoI signal was reduced by a factor of 5-6, falling below the detection level. In the following H-mode exposure the injection rate had to be increased to 2.8 Torr-l/s in order to achieve MoI signal suppression. In all cases, gas injection did not cause measurable perturbation of the global discharge and divertor plasma parameters.

Post-mortem RBS analysis [9] found the net erosion of molybdenum near the center of the samples of 1.0±0.5 nm on the sample from exposure #1 and less than the measurement resolution of 0.5 nm on the sample from exposure #2, corresponding to rates of 0.07±0.04 nm/s and < 0.04 nm/s respectively. Compared to the net erosion rates of 0.4–0.7 nm/s previously measured in L-mode discharges similar to those used in exposure #1 [10], this constitutes a reduction of 6–10X. However, since sample #1 was exposed at OSP for 1.5 s before the gas injection started in the first two discharges, part of the net erosion measured on that sample occurred without the injection. At the previously measured rates, net erosion during 1.5 s exposure in the first discharge alone would be expected at 0.6–1.05 nm, which accounts for 60–100% of the measured erosion. Thus the actual reduction of the erosion rate with $^{13}CH_4$ gas injection must have been more than 10X.

Visible carbon deposits were observed on both samples upon removal [Fig. 4(a,b)]. On the sample exposed in L-mode, the deposits formed a well-defined toroidal stripe, while on the sample exposed in H-mode, the deposition pattern was less regular, possibly due to effect of ELMs. Post-mortem NRA measured C deposition rates of ~32 nm/s in L-mode and ~8.5 nm/s in H-mode, assuming a deposited C density of 2 g/cm^3. Measured coverage of both ^{13}C and ^{12}C on the sample exposed in L-mode is shown in Fig. 5. Carbon coverage on the sample

exposed in H-mode was about 9 times lower. The ratio of $^{13}C/^{12}C$ carbon in the deposits was about 4-5 on both samples, indicating that the deposition was largely from the gas injection.

Post-exposure deuterium coverage on the exposed samples was also measured by NRA. The average D/C ratio on the sample exposed in L-mode was 0.39. On the sample exposed in H-mode, the average D/C ratio was ~0.14.

In the second experiment, the first exposure (#3) was completed with D_2 upstream gas injection, and the second one (#4) was with a $^{13}CH_4$ gas injection, both in three L-mode discharges with the plasma parameters similar to those of exposure #1. During exposure #3, D_2 injection started at 2.5 s into the discharge, then at 3.5 s the injection rate was increased [Fig.3(b)]. Temporal evolution of MoI signal at 390.2 nm measured by MDS spectrometer in the last exposure discharge is shown in Fig. 3(b). With the lower injection rate that had no measurable effect on the global discharge parameters, MoI signal was reduced by a factor of 3-4. With the higher injection rate, it went down to about the noise background level. Temporal evolution of T_e measured by the LP embedded in the sample is shown in Fig. 3(c). With the lower injection rate, T_e went down from ~35 eV to below 20 eV, then at higher injection rate it was further reduced to ~10 eV (scatter in the data is due to combination of the plasma fluctuations and poor I-V characteristic fits). The higher injection rate was slightly disturbing to the discharge, causing ~5% increase of the line-average density.

Exposure #4 was conducted in three reproducible discharges with $^{13}CH_4$ gas injection starting 0.5 s into the discharge, before the OSP was placed on DiMES. Gas injection was at the rate of 1.8 Torr-l/s, which was shown to suppress Mo erosion during exposure #1. The aim of this exposure was to repeat exposure #1 at constant reproducible conditions and with the local T_e measured by the embedded LP. This data set should be suitable to benchmark future modeling of the local erosion/deposition.

Post-exposure RBS showed net surface-average Mo erosion of ~9.3 nm on the sample exposed with D_2 injection. Measurable net erosion of Mo was expected, since the sample was exposed at the OSP for about 1.5 seconds before the start of the D_2 injection in each of the three exposure discharges. If it is assumed that Mo erosion only occurred before the D_2 injection, the average net erosion rate would be ~2 nm/s, which is a factor of 3-5 higher than previously reported for similar conditions without gas injection [10]. Considering that molybdenum erosion was still occurring at reduced rate during the lower rate D_2 injection in the first two exposure discharges, the pre-injection erosion rate was probably about 1-1.5 nm/s, which is still higher than reported previously. This discrepancy is being further investigated.

Mo erosion on the sample exposed with $^{13}CH_4$ gas injection was found to be below the RBS measurement resolution of 1 nm for this experiment. Deposition of ^{12}C and ^{13}C was measured by NRA with the corresponding surface-average deposition rates of ~4 nm/s and ~42 nm/s. Therefore, the ratio of $^{13}C/^{12}C$ in the deposits was even higher that in exposures #1 and #2, confirming that ~90% of the deposited carbon originated from the gas injection. D/C ratio in the deposits was measured at 0.27.

5. Summary

We have demonstrated that a local gas injection in the vicinity of a small area, high-Z PFC surface (molybdenum in our case) in a tokamak divertor can reduce or suppress surface erosion without globally disturbing the plasma discharge. Protecting larger surfaces will require larger gas injection levels, possibly perturbative. When a protective carbon coating was created by the methane gas injection, the erosion of Mo, fell below the limit of detection by spectroscopy. Post-exposure analysis of the samples by IBA also showed very low net erosion. We also tested erosion suppression with a non-depositing deuterium gas injection. While net erosion of Mo was not fully suppressed during D_2 gas injection, spectroscopic

measurements confirmed that the gross erosion was strongly reduced. Future experiments will be conducted to further quantify high-Z surface erosion reduction with non-depositing local gas injection.

Acknowledgment

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Figure captions

Fig. 1. Threshold electron temperature for transition from net deposition to net erosion of carbon as a function of the ratio of C to D fluxes to the surface, $f_C = \Gamma_C / \Gamma_D$, at different surface temperatures.

Fig. 2. Experimental setup showing LCFS, DiMES, and views of CMOS camera and MDS (a); image of the sample taken during exposure #1 by the camera with CD/CH filter (b)

Fig. 3. Temporal evolution of MoI signal at 390.2 nm measured by MDS spectrometer with $^{13}CH_4$ gas injection in exposure #1 (a) and with D_2 gas injection in exposure #3 (b). Temporal evolution of T_e measured in exposure #3 by the LP embedded in the sample is shown in (c).

Fig. 4. Post-exposure photographs of the samples exposed with $^{13}CH_4$ gas injection in exposures #1 (a), #2 (b), and #4 (c).

Fig. 5. Post-exposure ^{12}C and ^{13}C coverage of the DiMES sample from L-mode exposure #1.

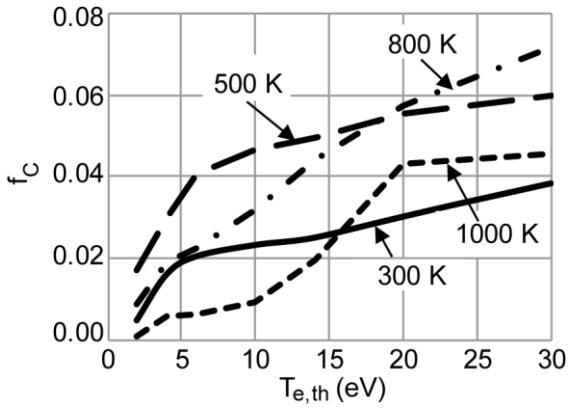
0.08
0.06
0.04
0.02
0.00
f_C
0
5
10
15
20
25
30
$T_{e,th}$ (eV)
800 K
500 K
1000 K
300 K

Fig. 1

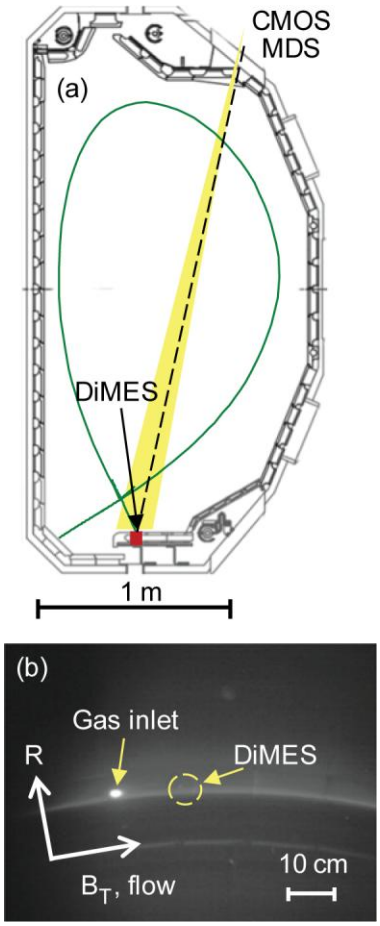

Fig. 2

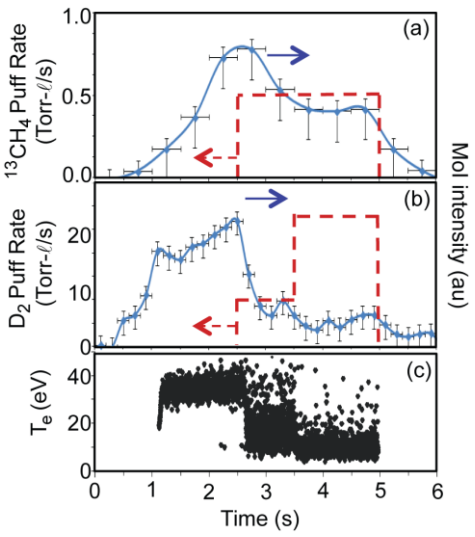
(a)
(b)
(c)
$^{13}CH_4$ Puff Rate (Torr-ℓ/s)
D_2 Puff Rate (Torr-ℓ/s)
T_e (eV)
Mol intensity (au)
Time (s)
1.0
0.5
0.0
20
10
0
40
20
0
0
1
2
3
4
5
6

Fig. 3

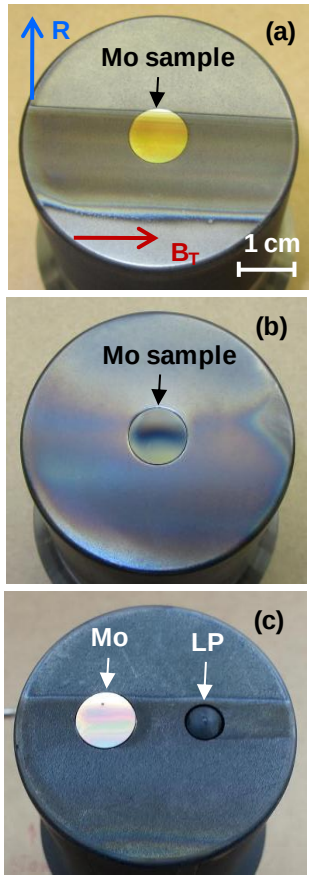

Fig. 4

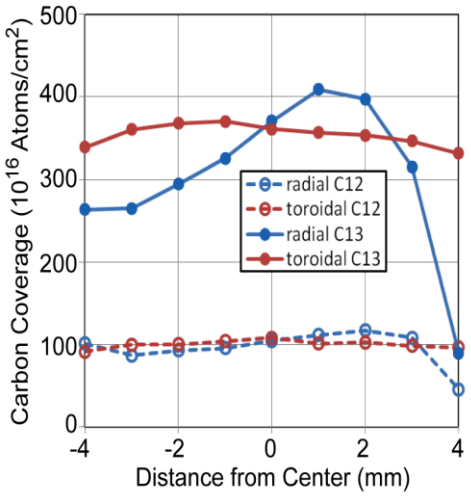
Carbon Coverage (10^{16} Atoms/cm^2)
500
400
300
200
100
0
-4
-2
0
2
4
Distance from Center (mm)
radial C12
toroidal C12
radial C13
toroidal C13

Fig. 5