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Erosion in the DIII-D divertor by neon-detached plasmas

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Abstract

We report the first measurements of erosion of divertor materials by plasmas detached by neon injection. Neon injection cooled the plasma edge by radiation, reduced the temperature and increased the density of the divertor plasma, and reduced the peak heat flux onto the divertor plate, while maintaining good H-mode energy confinement and purity of core plasma. The rate of carbon erosion at the outer strike point was very high ($\sim$15 nm/s), in contrast to the absence of erosion from plasmas detached by deuterium injection observed in previous experiments. The erosion rate for tungsten and vanadium remained low for neon-detached plasma. A likely cause of the high net carbon erosion rate is physical sputtering by neon, chemically enhanced by the formation of hydrocarbons.

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1. Introduction

Fusion reactor operating scenarios with detached plasmas are being considered to reduce the peak heat flux onto the divertor [1]. Another potential benefit of detached plasma operation is reduced erosion by sputtering due to lower energy of particles from the cool detached plasma. Detachment can be induced by puffing deuterium gas into the plasma edge, producing a high neutral density in the scrape-off-layer (SOL) [2], or by injecting impurities such as neon or argon gas which cools the plasma edge by radiation [3].

The ability to better withstand disruptions makes carbon-based materials attractive for use in the divertor [4]. However, carbon-based materials suffer high erosion rates during attached plasma operation, which in a high performance experimental reactor, would result in short component lifetimes and high tritium inventories [4,5]. Here we present new results from an experiment in DIII-D, in which the divertor materials evaluation system (DiMES) [6] was used to measure erosion and deposition in the divertor with detached H-mode plasmas. These studies have previously shown [7] that with plasmas detached by deuterium gas puffing, net erosion is suppressed everywhere in the divertor, the divertor plasma electron temperature is low ($T_e < 2$ eV) and physical sputtering is eliminated. Here we report the first measurements of erosion rates of materials exposed to plasmas detached by neon injection. These experiments show that although the peak heat flux at the outer strike point (OSP) was reduced by neon injection, the rate of carbon erosion was very high ($\sim$15 nm/s), in contrast to the absence of erosion from plasmas detached by deuterium injection. This result shows that the rate of carbon erosion by detached plasmas strongly depends on how detachment is achieved. The results from these experiments will help guide the choice of plasma-facing materials and operating conditions for the next generation of fusion experiments.

2. Experiment

DiMES was used to expose a sample to well defined plasmas for short periods at the DIII-D lower divertor

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plate and retrieve it for analysis of the resulting erosion or deposition of material [6]. The sample consisted of a 5 cm diameter cylinder of ATJ (Union Carbide) graphite. During exposure, the flat end of the sample was flush with the surrounding graphite divertor tiles, making the sample part of the divertor floor.

All plasma exposures were done with lower single null divertor plasma configuration. The outer divertor strike point was moved onto the probe during steady state periods of the plasma. Probe D100 was exposed to six similar H-mode plasmas giving a total exposure time of 17 s. Plasma conditions at the DiMES location were determined by Langmuir probes in the divertor floor, and by Thompson scattering, spectroscopy, infrared thermography and other diagnostics.

Fig. 1 shows the plasma conditions during exposure of D100. Neon was injected, initially at a higher rate for 200 ms followed by a low but steady rate. This produced good quality H-mode confinement, with a reduced peak heat flux (by a factor of about 2.5) at the OSP. During detachment the divertor plasma fluctuated between a predominant low temperature ($T_e = 1.5$–4 eV) high density state and a less frequent higher temperature ($T_e = 12$–30 eV) lower density state, as shown in Fig. 2. The plasma was in the high temperature state 20–30% of the time. This fluctuation did not occur for plasmas detached by deuterium injection. During the detached portion of the discharge, the fraction of power radiated increased significantly, while the concentration of neon in the core plasma was small (~0.5%) and Z_{eff} remained low (<2).

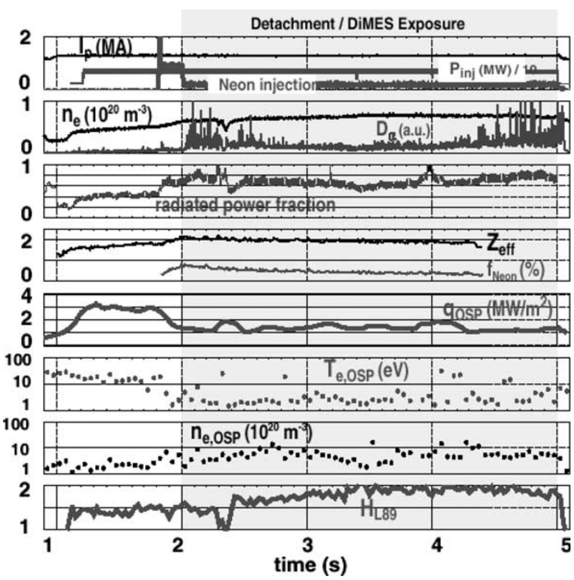

Fig. 1. Neon-detached plasma conditions. Neon injection begins at 1.8 s. The OSP is moved onto the DiMES probe at 2 s and off at 5 s.

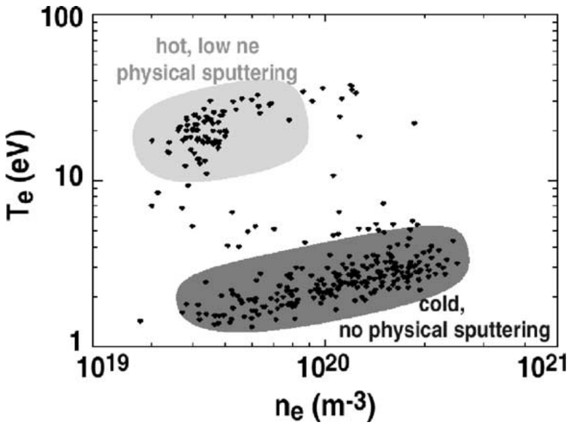

Fig. 2. The divertor plasma temperature T_e and density n_e (determined by Thompson scattering) fluctuated between cool higher density and warm lower density states.

The mass or number of atoms per unit area (areal density) of the various materials deposited on or eroded from the samples was measured by MeV ion backscattering for carbon and metals, and by nuclear reaction analysis for deuterium and boron [8]. The net carbon erosion/deposition was determined from the change in depth of an implanted depth marker of silicon, initially 320 nm beneath the surface. The resolution of the measurement of net carbon erosion is ±10 nm. Fig. 3 shows the net carbon erosion along a line in the radial direction passing through the center of the probe. The erosion peaks near the location of the separatrix at a value of 250 nm. For comparison, Fig. 3 also shows the net carbon erosion and deposition measured previously

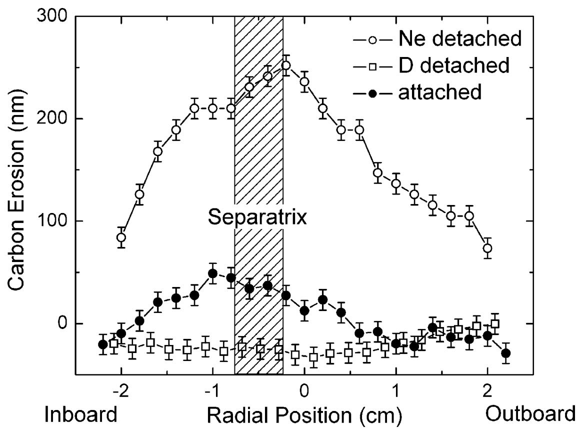

Fig. 3. Measured net carbon erosion along a line in the radial direction. The shaded region indicates the location of the OSP separatrix. Negative values correspond to net deposition. Open circles for neon-detached plasma 17 s exposure (D100), open squares for deuterium detached plasma 13 s exposure (D73), filled circles for attached plasma 18 s exposure (D79).

along the same line on two similar samples, D73 exposed at the OSP for 13 s to plasma detached by deuterium injection [7], and D79 exposed for 18 s to attached plasma [5,9]. Fig. 4 shows the net carbon erosion along a line in the toroidal direction through the center of the probe. Here the carbon erosion is mainly in the range from about 200 to 250 nm.

Tungsten and vanadium films ~100 nm thick were deposited on the surface of D100 in 3 × 30 mm stripes to examine the erosion rate for metals. The change in thickness of W and V films was less than the resolution of the measurement (5% or 5 nm), i.e. less than 2% of the erosion of the carbon. Another test for metal erosion is the presence of metal redeposited onto the carbon surface adjacent to the metal films [10]. Fig. 5 shows the coverage of tungsten on the probe along a line in the radial direction through the center of the probe. For comparison, the tungsten coverage is also shown on similar probes exposed at the OSP to plasmas detached by deuterium injection (D73) [7], and to attached plasma (D79) [5,9]. The W coverage on the probes exposed to detached plasmas was close to the limit of detection of 10^{13} atoms/cm^2, but was about 100 times higher on the probe exposed to attached plasmas.

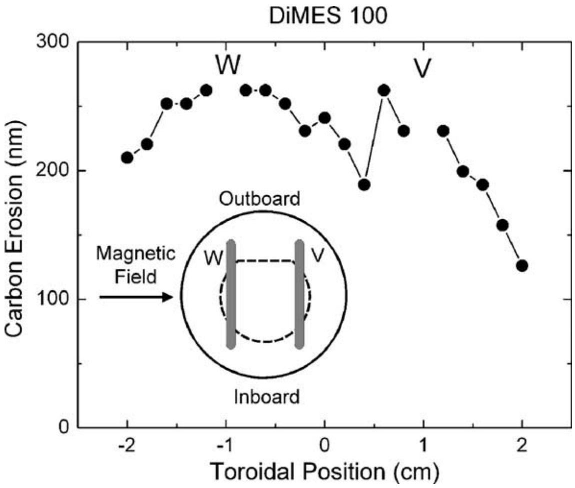

Fig. 4. Measured net carbon erosion along a line in the toroidal direction on the probe exposed to neon detached plasma. The inset diagram shows the location of the tungsten and vanadium metal films.

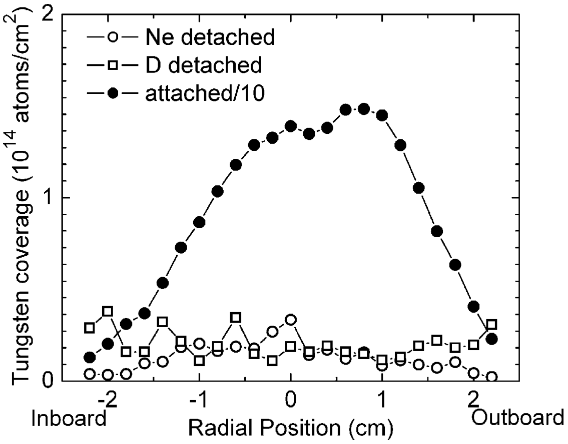

Fig. 5. Tungsten coverage along a line in the radial direction on probes exposed at the OSP to attached plasma (D79 open circles) and plasmas detached by injection of neon (D100 solid circles) and deuterium (D73 open triangles).

3. Discussion

The rate of carbon erosion by neon-detached plasma is very high, 15 nm/s, in contrast to the absence of erosion by plasma detached by deuterium injection. This carbon erosion rate is also much larger than the 3 nm/s peak erosion rate previously measured at the OSP for attached ELMing H-mode plasma in DIII-D (D79) [5,9]. A likely cause of the high net carbon erosion by neon-detached plasmas is sputtering by the neon [11].

The kinetic energy of ions striking the surface should be the thermal energy (3/2 kT_i) plus the energy gained by acceleration through the sheath ($\sim Z\ 3\ kT_e$), plus energy due to plasma flow. The energy due to plasma flow is $(M_{Ne}/M_D)\ kT_i = 10kT_i$, for neon in a primarily D plasma flowing at the sound speed. The plasma should be close to thermal equilibrium ($T_i \sim T_e$). The average charge state (Z) of neon ions should be close to one for low temperature detached plasma. The energy of neon ions striking the divertor should therefore be $E_{Ne} \sim 14kT_e$, predominantly due to the plasma flow. This gives neon energies in the range from 20–50 eV for the lower temperature plasma state ($T_e = 1.5$–4 eV), and in the range from 175–350 eV for the higher temperature plasma state ($T_e = 12$–30 eV, see Fig. 2).

Yields for physical sputtering of carbon by neon at normal incidence are 0.1–0.2 C/Ne for energies corresponding to the higher temperature state, and are predicted to be very small for the low temperature state for which the ion energy is below the threshold (70 eV) for sputtering [12]. However, sputtering yields on a carbon divertor are likely to be higher than these values, particularly at low energies, for two reasons. First, neon ions strike the divertor surface at oblique angles of incidence which results in lower threshold energies and higher sputtering yields [13]. Second, the high flux of deuterium onto the divertor forms hydrocarbons which are less strongly bound than atomic carbon. Kinetic ejection of hydrocarbon complexes from the surface by collisional energy transfer results in much higher effective sputtering yields at low energies [14]. Threshold energies for sputtering by this process are estimated to be only 1 or 2 eV [14] instead of 70 eV for neon at normal incidence on carbon [12]. These two effects might result in carbon sputtering yields of order one for neon from the higher temperature plasma state and possibly also for the lower temperature state.

The sputtering yield of tungsten by neon is predicted to be about 0.2 W/Ne for the higher temperature plasma state and very small for the lower temperature plasma state [12]. In contrast to carbon, the sputtering yield of metals should not be significantly enhanced by chemical effects.

The flux of neon required to produce the observed rate of carbon erosion ($\Gamma = 15$ nm/s) is $\Phi_{Ne} = \Gamma N_C/Y = 1.5 \times 10^{21}/m^2\,s$, where $N_C = 10^{29}/m^3$ is the atomic density of carbon and using a sputtering yield of $Y = 1$ C/Ne. The average ion flux onto the OSP, measured by a Langmuir probe, was about $10^{23}/m^2\,s$. Thus, a neon flux of 1.5% of the total ion flux could produce the observed carbon erosion, assuming a sputtering yield of one during the entire exposure and no carbon redeposition. If sputtering occurs only during exposure to the high temperature state, the effective exposure is about 25% of the time and the neon flux would need to be 6% of the total ion flux to give the observed erosion rate. These fractions are higher than the concentration of neon in the plasma (see Fig. 1). However, the neon flux onto the surface could be much higher than the neon flux in the SOL due to local recycling of neon at the divertor [11].

In addition to the flux of carbon from the divertor surface there will also be a flux of carbon onto the surface from the plasma. The measured net erosion rate is the difference between these two fluxes, i.e. the gross erosion minus the deposition. The gross erosion rate is therefore higher than the measured net erosion, and the incident neon flux to give the observed net carbon erosion also would be correspondingly higher than estimated above. Quantitative modeling of net erosion incorporating carbon deposition and local neon recycling requires detailed computer simulation of impurity transport in the edge plasma which is beyond the scope of this paper [11].

4. Summary

Detachment by neon injection, instead of deuterium gas injection, enables reduced divertor heat flux while maintaining reasonable purity of core plasma, lower neutral density at the edge and good H-mode confinement. Neon injection cooled the plasma edge by radiation, reduced the temperature and increased the density of the divertor plasma at the OSP. However, it was found that the net erosion rate of carbon at the OSP was very high (15 nm/s) with neon-detached plasma, in contrast to the absence of erosion from plasmas detached by deuterium injection. The erosion rate for tungsten and vanadium remained low for neon-detached plasma. A likely cause of the high net carbon erosion rate is physical sputtering by neon, chemically enhanced by formation of hydrocarbons.

Acknowledgements

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