



Ion flux dependence of atomic hydrogen loss probabilities on tungsten and carbon surfaces



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ARTICLE INFO

Article history:

Received 6 December 2013

Accepted 30 March 2014

Available online 5 April 2014

ABSTRACT

Concerns over fuel inventory and consequently radiation safety in a fusion device necessitates a better understanding of complex plasma–material interactions. Pulsed induced fluorescence is employed to determine the loss probability of atomic hydrogen on graphite and tungsten in a low-pressure radio-frequency discharge with an applied magnetic field. The interaction between the plasma and sample material surface leads to a two-stage decay in the atomic hydrogen loss rate in the plasma afterglow, from which the loss probability is determined. The loss rates are found to be dependent on the ion flux. An increase in the ion flux from $1.6 \times 10^{20} \text{ m}^{-2} \text{ s}^{-1}$ to $5.5 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$ leads to an increase in the loss probability by a factor of two for both graphite and tungsten in the near afterglow. The results demonstrate that the plasma operating conditions play an important role in the loss probability of atomic hydrogen at surfaces of fusion-relevant materials.

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1. Introduction

Of crucial importance to the success of the international experimental fusion reactor, ITER, and steady state fusion devices, is the choice of suitable materials for the divertor region [1]. Understanding and controlling the complex interactions between the plasma edge and the wall underpins future fusion technology [2,3]. The interaction between hydrogen isotope plasmas (H, D, T) and a range of specific materials, most notably tungsten and graphite, is of particular importance. An important area of concern for confined fusion reactors is fuelling, recycling, and hydrogen inventory in material. The surface loss probability can provide information on hydrogen inventory in the walls and is an important input value for modelling tokamak-edge-plasmas [4]. It takes into account the total loss including diffusion into the bulk of the material, sticking coefficient, surface recombination and erosion. Recent simulations of hydrogen discharges have shown that the atomic hydrogen loss probability can have a significant impact on the steady-state densities of reactive species in the plasma [5]. Despite this, the loss probabilities of only a small number of materials have been measured and only for a very narrow range of plasma operating conditions.

The surface loss probability, γ , dictates the rate at which a species is lost onto a particular material surface. For atomic hydrogen, the total loss rate from the bulk plasma to the walls is given by: [5]

$$R_{\text{rec}} = \frac{A_0^2}{D_H} + \frac{2V}{A\bar{v}_H} \frac{2 - \gamma}{\gamma} \quad (1)$$

The first part of the right-hand side of equation 1 corresponds to the diffusion of hydrogen atoms to the wall, which depends on the effective diffusion length, A_0 , and the atomic hydrogen diffusion coefficient, D_H . The second part describes the recombination at the walls and depends on the reactor volume, V , the wall surface area, A , and the thermal speed of atomic hydrogen, $\bar{v}_H$, as well as γ . In general, recombination is very efficient for metals and less so for Pyrex and quartz [6]. Measurements have shown that γ can be significantly altered by reactor wall temperature [7], the presence of an oxide layer on reactor surfaces [8], the process of wall passivation [9], the previous exposure of the surface to a plasma [10] and general surface cleanliness [11].

Recent work by Drenik et al. [12] measured a hydrogen recombination coefficient of 10^{-3} on amorphous carbon using a fibre optic catalytic probe in an inductively coupled radio-frequency plasma for one operating condition of applied input power. In this paper, we measure the loss probability of atomic hydrogen for a number of materials in a low-pressure magnetically enhanced plasma. By varying the plasma operating conditions, we show that the loss probability is dependent on the ion flux to the surface.

2. Experimental set-up

The measurements were performed in the MAGnetized Plasma Interaction Experiment (MAGPIE): a linear magnetically-enhanced

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Helicon reactor designed to investigate the interaction between plasmas and material surfaces in a fusion-relevant environment. In hydrogen plasma discharges, MAGPIE achieves densities up to 10^{19} m^{-3} with an electron temperature of 3–6 eV [13]. The experimental setup is shown in Fig. 1a and has been described previously [13,14]. For the present measurements, a 50 cm long, 9 cm inner diameter borosilicate tube was inserted into the target chamber to create a low loss background surface. A small magnetic field was produced in the chamber by applying 50 A to the source solenoids and 100 A to the target solenoids. This magnetic configuration produces a field with strength of approximately 50 G in the source region and at the sample surface. The magnetic field lines for this configuration are shown in Fig. 1. A directional coupler measured applied RF power up to 1000 W and the pressure was maintained at 10 m Torr. The plasma is operated in pulsed mode with a plasma discharge duration of 10 ms and duty cycle of $\sim 2\%$ to maintain minimal sample heating. Optical emission spectroscopy and Langmuir probe measurements ensured that the plasma reached a steady state over the 10 ms duration. An Impedans [15] Langmuir probe system was used to determine the ion flux by measuring the ion density and electron temperature in a continuous discharge. The ion flux parameter range explored here for various applied powers is shown in Fig. 2. The ion flux increases from $4 \times 10^{19} \text{ m}^{-2} \text{ s}^{-1}$ at 200 W to $9 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$ at 1000 W.

In these experiments polycrystalline tungsten and fine-grain graphite foils of 99.95% purity were employed. Target samples with a diameter of 8.5 cm were attached to the front of a 1.5 cm diameter stainless steel sample holder and inserted into the borosilicate tube approximately 15 cm from the source-diffusion chamber interface. This setup guaranteed no contribution from the sample holder itself. For comparison, a “control case” was implemented,

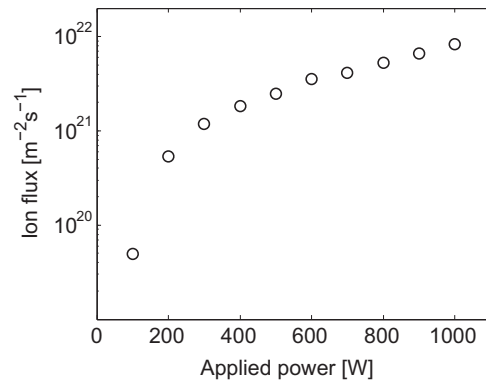


Fig. 2. The ion flux dependence on applied power in the MAGPIE device at 10 m Torr.

whereby the sample holder was completely removed from the target region. The main contribution to the loss probability is now from the 1.6 m long borosilicate tube with the end plates at both extremities ($z = 0.68 \text{ m}$ and $z = -1 \text{ m}$) having negligible influence. Prior to all measurements, a pulsed hydrogen plasma was run for 40 min so that the chamber reached a steady state.

3. Pulsed induced fluorescence

The loss probability is measured directly using a spectroscopic technique called Pulsed Induced Fluorescence (PIF). The PIF technique was pioneered by Bouchoule and Ranson [16] to study the loss probability of atomic hydrogen onto Pyrex and quartz reactor

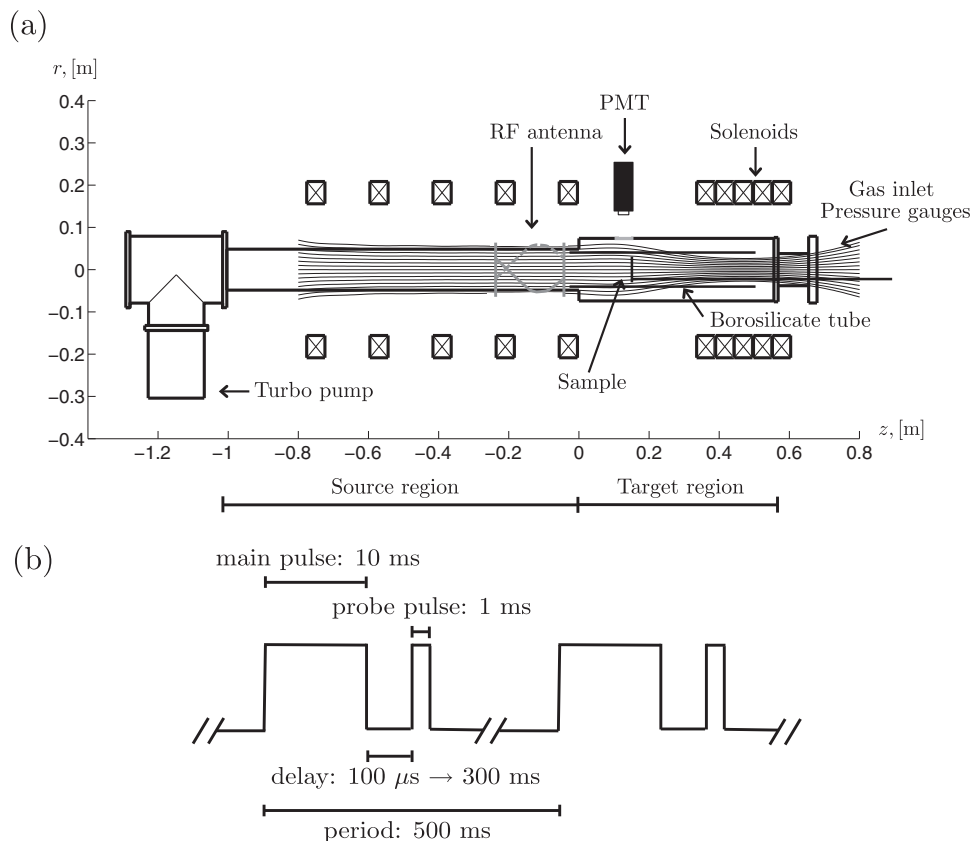


Fig. 1. (a) Experimental setup of the MAGPIE reactor as configured for the measurements described here. The magnetic field lines are shown for 50 A current applied to the source solenoids and 100 A applied to the target solenoids. (b) RF modulation scheme used for PIF measurements.

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