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Characterization of a neutral atomic hydrogen source developed in the perspective of carbon materials etching study

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ABSTRACT

This paper deals with the characterization of an atomic hydrogen source created in a radio-frequency reactor with a helicon configuration. To achieve this purpose, optical (laser induced fluorescence) and electrical (Langmuir probe) diagnostics are used to monitor the behavior of the species composing the plasma. The influence of pressure, gas composition, and impact of the magnetic fields (in the source and diffusion chambers) are investigated.

1. Introduction

Successful future fusion devices require longer confinement times for their fusion plasma. However, confinement being imperfect, such plasma interacts strongly with the walls of the device, eroding them physically and chemically. In particular, carbon material walls such as carbon fiber composites are strongly eroded, which results in dust formation and fuel retention [1], causing strong safety problems due to tritium radioactivity. Since these phenomena are unavoidable, the objective is to limit them. However, etching and carbon wall modification processes, especially chemical ones, are still not well understood.

In this paper we present the characterization of an atomic hydrogen source dedicated to the study of chemical erosion of carbon materials by atomic hydrogen. This source uses a radio-frequency (RF) plasma reactor with a helicon configuration and a H_2/Ar gas mixture at low pressure (0.05–0.7 mbar). The use of a plasma instead of thermal decomposition [2,3] for example to create atomic hydrogen has several advantages. First, since H_2 is dissociated by electron collisions, the gas remains cold, contrary to atomic hydrogen created in a heated tungsten capillary. Moreover, in the H_2/Ar mixture, the source generates in the same time as the heavy ion (Ar^+) and atomic hydrogen, thus allowing for the synergistic effect between physical and chemical sputtering which is present in the edge plasma of tokamaks. Plasma can also generate atomic hydrogen in measurable quantity at very low pressure (less than 0.1 mbar). Finally, atomic hydrogen diffusion is isotropic in a plasma source, contrary to a particle-beam device where the source can be considered as a point source, which is inappropriate when etching 20×20 mm substrates homogeneously.

Two photon absorption laser induced fluorescence (TALIF) and Langmuir probe are used to monitor, respectively, the neutral atomic hydrogen and electron density and temperature. The influence of the working parameters such as pressure, gas mixture, and magnetic fields on atomic hydrogen density is studied.

2. Experimental apparatus

2.1. The RF reactor

The experiments were carried out in a plasma reactor with helicon geometry presented in Fig. 1. It is composed of a source chamber, which consists of a Pyrex tube, and a stainless steel diffusion chamber that is 320 mm in diameter and 250 mm in height. The plasma is generated by a double saddle type helicon antenna [4] surrounding the source chamber. The input 13.56 MHz RF power (P_{RF}) ranges up to 1000 W. Static magnetic fields are generated by two sets of copper coils, respectively around the source and diffusion chambers, with values up to 200 G in the source chamber (B_{source}) and 100 G in the diffusion chamber (B_{diff}). Plasma is created in an H_2/Ar gas mixture, and the proportion of H_2 (H_2%) is also a working parameter.

Depending on the experimental configuration, different coupling modes can be achieved in this reactor. In Fig. 2 we illustrate their appearance with different plasma photographs. If power is low enough and/or pressure is relatively high, we obtain the capacitive mode [5], with an electron density n_e around 10^8-10^9 cm^{-3} in the center of the diffusion chamber. With higher power and/or lower pressure, and weak B_{source} (≤20 G in 5.10^{-3} mbar pure argon plasma), the inductive mode [5] is achieved, with a relatively homogeneous plasma column, and with n_e around $10^{11}-10^{12}$ cm^{-3}. In the case of higher B_{source}, Trivelpiece–Gould (TG) mode [6] is reached, recognizable by its ring distribution, with weak plasma in the center of the diffusion chamber (n_e around 10^9-10^{10} cm^{-3}). Finally, for particular P_{RF}/B_{source} couples, resonant TG mode [7] occurs. It is the same as the TG mode with the

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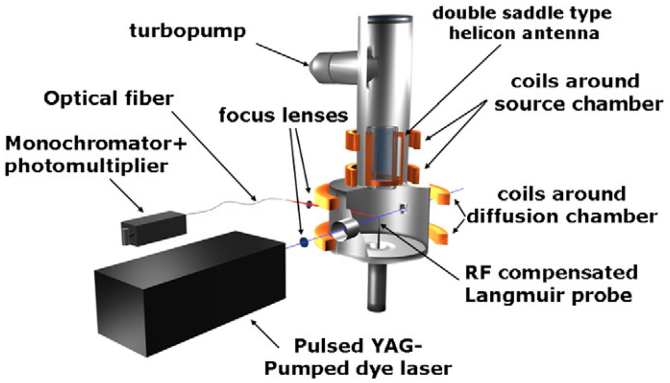

Fig. 1. Experimental apparatus set-up diagram with the TALIF and Langmuir probe plasma diagnostics configuration.

addition of a small cylinder of luminous plasma along the axis of the diffusion chamber, and its corresponding n_e ranges around 10^{10}–10^{11} cm^{-3}. One can remark that due to the limitation in RF power, helicon mode is not reachable in this reactor.

The multiplicity of possible RF coupling, very sensitive to experimental parameters, make in consequence the characterization of this reactor very complex.

2.2. Diagnostics

Two-photon absorption laser induced fluorescence (TALIF) [9,10] was performed to measure the relative atomic hydrogen density $[H^g]_{rel}$ through the following scheme:

$$\begin{aligned}H(n=1)+2h\nu_l &\rightarrow H(n=3)\\ &\rightarrow H(n=2)+h\nu_f\end{aligned}$$

where $h\nu_l = 6.05$ eV ($\lambda_l = 205$ nm) and $h\nu_f = 1.89$ eV ($\lambda_f = 656.3$ nm) are the laser and fluorescence photon energy respectively.

A pulsed YAG-pumped dye laser (QUANTEL) operating with rhodamine 640 as the dye is used (cf Fig. 1). After being focused by a lens to increase the two photons absorption probability, the laser beam enters through the front window. The subsequent fluorescence is detected at 90° through a side window. The detection part is composed of a focus lens, an optical fiber (2 m length), a monochromator allowing to select the wavelength, and finally a photomultiplier. This optical arrangement is important to place the photomultiplier away from the reactor, thus limiting any RF radiation perturbation. The signal obtained is then gate-integrated over the duration of the fluorescence signal and averaged by means of a "boxcar-averaged gated integrator" from Stanford Research Systems. Experiments are performed at relatively low pressure (≤1.5 mbar). Thus, the fluorescence signal is assumed to be proportional to ground state H-atom density which, without calibration possibility, is only relative.

Finally, electron characteristics, especially the electron density n_e and temperature T_e, are measured using a SmartProbe® RF compensated Langmuir probe from Scientific Systems Ltd. Its working principle and the underlying theory can be found in [8]. It is placed on the axis of the reactor (Fig. 1), following the magnetic field lines to limit perturbations. Measurements are taken just below the laser beam, at the center of the diffusion chamber. Acquisitions and treatments are performed using the Smartsoft software provided with the probe.

3. Results and discussion

First measurements were achieved at 5.10^{-3} mbar (typical working pressure in such helicon configuration reactor in pure argon). However, whatever the other experimental parameters, measurements of $[H^g]_{rel}$ remained very low. Thus, the influence of pressure increase on $[H^g]_{rel}$ was investigated.

First of all, the influence of the presence or not of B_{source} is studied, since B_{source} can produce TG or resonant TG modes which have a great influence on n_e. Fig. 3 presents n_e as a function of pressure for $B_{source} = 0$ and 80 G and two H_2% (10% and 50%) in the gas mixture. P_{RF} is fixed at 600 W. Concerning the impact of B_{source} on n_e, one can see that for both H_2%, there is no significant change for n_e with or without B_{source}. This implies that the resonant TG mode does not occur and therefore that B_{source} has a limited influence while working in this range of pressure. Thus, B_{source} is not applied in the following experiments.

Concerning the pressure effect on n_e, Fig. 3 shows that, for the four sets of experimental parameters, increasing pressure induces a drastic decrease of n_e in the center of the diffusion chamber. This behavior can be explained by several processes. First, it was observed that increasing the pressure higher than 0.027–0.070 mbar (depending on the gas mixture) leads to a transition from inductive to capacitive mode. This is responsible for the first strong decrease of one decade of n_e for both H_2%. Then, of course, increasing the pressure limits the plasma expansion from the source chamber to the diffusion one. This is mainly due to inelastic electron collisions with the gas species in the vicinity of the antenna, since the mean free path of electrons decreases with pressure (picture in Fig. 2(a) taken at 0.040 mbar in pure argon). Moreover, these collisions, increasing with the pressure, could induce a decrease of ionization in the source chamber. For pressures higher than 0.130 mbar, the very low n_e and corresponding T_e (Fig. 4) measured in the center of the diffusion chamber confirm that we have a diffusive plasma. Consequently, it can be assumed that the species production processes mainly occur in the source chamber, close to the antenna, especially in the capacitive mode.

Fig. 5 shows TALIF measurements representing $[H^g]_{rel}$ versus the pressure for three H_2%, at $P_{RF} = 600$ W, $B_{source} = 0$ G and $B_{diff} = 40$ G.

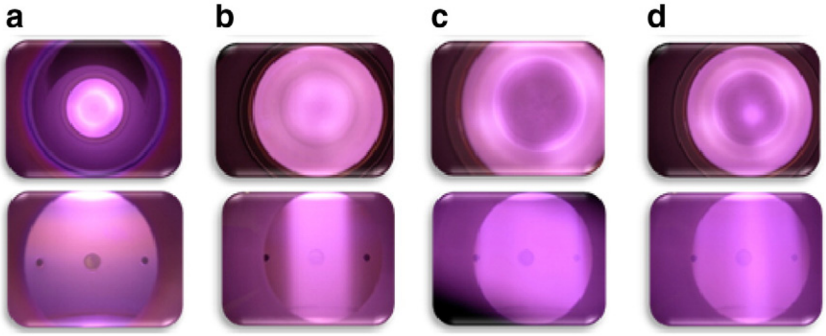

Fig. 2. Pictures taken from upper and front windows of the different coupling modes available in the reactor: (a) capacitive, (b) inductive, (c) Trivelpiece–Gould (TG), and (d) resonant TG modes.