Diagnostics of low-pressure hydrogen discharge created in a 13.56MHz RF plasma reactor

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Abstract
A 13.56 MHz RF discharge in hydrogen was studied within the pressure range of 1–10 Pa, and at a power range of 400–1000 W. The electron energy distribution function and electron density were measured by a Langmuir probe. The gas temperature was determined by the Fulcher-α system in pure H2, and by the second positive system of nitrogen using N2 as the probing gas. The gas temperature was constant and equal to 450 ± 50 K in the capacitively coupled plasma (CCP) mode, and it increased with pressure and power in the inductively coupled plasma (ICP) mode. Also, the vibrational temperature of the ground state of hydrogen molecules was determined to be around 3100 and 2000 ± 500 K in the ICP and CCP mode, respectively. The concentration of atomic hydrogen was determined by means of actinometry, either by using Ar (5%) as the probing gas, or by using H2 as the actinometer in pure hydrogen (Q1 rotational line of Fulcher-α system). The concentration of hydrogen density increased with pressure in both modes, but with a dissociation degree slightly higher in the ICP mode (a factor 2).

Keywords: RF discharge, hydrogen discharge, plasma-wall interactions, optical emission spectroscopy

(Some figures may appear in colour only in the online journal)

1. Introduction
In tokamaks (nuclear fusion reactors), a hot plasma composed of deuterium and tritium nuclei is magnetically confined to achieve fusion to produce energy. The ITER tokamak project aims to demonstrate the feasibility of producing energy, while the DEMO reactor aims to be the first fusion reactor prototype to deliver power to the electric network. The present project is put into the context of these international projects. In tokamaks, the core plasma is hot, about 1–10 keV, and the edge plasma is colder and has a temperature of a few eV, depending on the tokamak. The edge plasma, despite being colder, strongly interacts with the walls of the machine. Particular parts of the walls, e.g. divertors, are subjected to high heat and particle fluxes, leading to material erosion. Considering the case of erosion, divertors made of low atomic number (low-Z) material have, until now, been preferred due to the limit of energy loss by radiation. During recent years, graphite has been studied extensively, as the material of which divertors could be composed, due to its invaluable thermal and mechanical properties (Richou et al 2007, Martin et al 2011, Pardanaud et al 2011, Tsitrone et al 2011, Pardanaud et al 2012, Bernard et al 2013, Pardanaud et al 2013, Mellet et al 2014, Pardanaud et al 2014). However, severe drawbacks in the form of the high retention of tritium (Roth et al 2009, Pegourie et al 2013) and low resistance to neutron bombardment as well as erosion and co-deposition of hydrocarbons in shadowed areas mean that graphite will never be used as a divertor material in fusion reactors. Therefore, current research focus is devoted to high-Z materials, with tungsten being considered as the most appropriate candidate. As it stands, both the German tokamak ASDEX...
upgrade (Hermann and Gruber 2003) and the European JET (EUROfusion JET), currently the most powerful tokamak in the world, are now using tungsten-coated divertors. Also the project WEST (Grosman et al 2013, Marandet et al 2014), aims to study and build a tungsten divertor in the tokamak Tore Supra at Cadarache. High-Z materials possess the advantage of having a high sputter threshold in hydrogen plasma, but at the cost of radiating huge power and extinguishing the plasma in the case of impurity events. To prevent tungsten erosion in the fusion reactor, it is crucial to reduce the heat load on the divertors to less than 10 MWm \(^{-2}\) in the steady state. Impurity gas seeding (N\(_2\), Ar, Ne...) is considered as the primary technique to decrease the heat load to the divertor.

In the fusion device, plasma-facing components play a major role in recycling species. The edge plasma physics and the plasma-wall interactions are important bottlenecks for the development of fusion energy. Current edge codes used for the ITER design process, such as SOLEDGE2D-EIRENE (based on a fluid approach for the plasma and on kinetic Monte Carlo simulations for neutral particles) (Ciraulo et al 2014), have only very limited ability to deal with mixed material environments (Bonnin et al 2009, Toma et al 2010), due to the lack of a comprehensive wall model. These codes can to some extent describe impurity migration in the machine, in order to simulate the change in the wall composition. But still, reliable data are not yet available for: thermal properties, sputtering yields and reflection coefficients for the resulting mixed materials. Among the data needed for simulation codes, atomic H reflection by a surface under plasma exposure is a key parameter playing a strong role in the process of hydrogen recycling at the plasma wall (Brezinsek et al 2005, 2003). Under the detached plasma conditions that will be encountered at the ITER divertor, ion energy is below 20 eV. The TRIM code (Eckstein 1991), which was used in the past to calculate atomic H reflection coefficients, is no longer useful since it is based on the binary collision approximation which ceases to be valid below a few tens of eV. More recent calculations use molecular dynamic (MD) simulations (Henriksson et al 2006, Inagaki et al 2011) instead of TRIM calculations to determine the reflection probability at low energy. As MD simulations rely on a calculated interaction potential, results obtained must always be benchmarked with experiments. Finally, none of these calculations takes into account impurity seeding. Therefore, we have developed a dedicated laboratory plasma experiment to measure the hydrogen (or deuterium) reflection coefficient and its dependence on various parameters (impurities, wall temperature, ion flux, atomic flux...).

The present paper deals with the characterization of the above-mentioned hydrogen plasma source, which is required before any measurement of the reflection coefficient. Let us note that this thematic of atomic loss (or atomic reflection) on the surface is not only limited to fusion-related studies, but concerns most of the low-pressure plasma processes. The measurement of the reflection coefficient and its dependence with experimental parameters is a recurrent issue in many plasma applications, ranging from microelectronics to fusion, as evidenced by the high number of papers dealing with this subject over decades (Wood and Wise 1962, Cartry et al 2000, Rousseau et al 2001, Lopaev and Smirnov 2004, Macko et al 2004, Kuruczi et al 2005, Bousquet et al 2007, Guerra 2007, Mozetic and Cvelbar 2007, Kang et al 2011, Rutigliano and Cacciatore 2011, Jacq et al 2013, Samuell and Corr 2014, Sode et al 2014, Marinov et al 2014a). Finally, hydrogen plasma characterization is of interest not only because of the atomic surface loss issue, but because hydrogen gas is often used for plasma processing such as hydrogenation (Hatano and Watanabe 2002), the treatment of Si wafers for creating subsurface defects in layers (Ghica et al 2010), chemical vapor deposition of diamonds (Hassouni et al 1996), functional materials or polycrystallization of amorphous Si, and the creation of positive (Liu and Fonash 1993, Cielaszyk et al 1995) or negative ions in ion-sources (Iordanova et al 2011, Kalache et al 2004, Ahmad et al 2013).

In this work, we characterize the RF plasma source in capacitively coupled plasma (CCP) and inductively coupled plasma (ICP) modes by studying primarily a pure hydrogen plasma. We determine gas temperature using optical emission spectroscopy under nitrogen admixture, electron density and temperature using a Langmuir probe, vibrational temperature of the ground state of hydrogen by using a Fulcher-α emission system, and atomic hydrogen concentration using actinometry under argon admixture. All measurements were realized versus pressure (1–10 Pa) and delivered power (400–1000 W) in continuous discharge or pulsed mode. The experimental apparatus is first described, and followed by the description and discussion in particular subsections of the methods and the experimental results obtained.

2. Experimental set-up and measurement conditions

The scheme of the experimental set-up is given in figure 1. The plasma source consists of a spherical stainless steel chamber 300 mm in diameter. A planar coil antenna (three turn) is separated from the plasma by a quartz window (166 mm in diameter, 12 mm thick) placed on top of the plasma chamber. The antenna is connected to an L-type matching box connected to an Advanced Energy Cesar 1310 RF generator. The plasma chamber is made of stainless steel with Pyrex and quartz windows and a molybdenum sample holder. The gas is introduced into the plasma chamber through mass-flow controllers and pumped thanks to a 5501 s\(^{-1}\) turbomolecular pump followed by an oil rotary pump. The base pressure in the plasma chamber is 10\(^{-6}\) Pa (measured by an ionization gauge). We studied pure hydrogen plasma at powers of 400, 600, 850 and 1000 W and at pressures from 1–10 Pa. The pressure during the plasma is measured by a capacitive gauge and is regulated by changing the pumping speed by modifying a gate valve opening placed between the plasma and the turbomolecular pump.

A sample holder from the Vegatec company is used to hold 4" wafers. The sample holder allows for wafer temperature measurement thanks to a backside thermocouple, wafer
heating and cooling (from room temperature to 800 °C) using a backside resistive heater and backside circulation of fluid (air or glycol-based liquid), wafer loading and clamping (the chamber is equipped with a load lock chamber), and biasing of the wafer down to −1 kV. The sample holder can be translated vertically. It was adjusted in a way so that the surface of the sample would be at the 0 cm position in figure 1. In order to limit the plasma expansion and better define the wall conditions for the surface loss measurements, a moving Pyrex tube (external diameter 170 mm, thickness 5 mm, height 146 mm) has been installed in the plasma chamber. When the tube is in the upper position, the plasma is confined by the tube itself, with the Al₂O₃ window on the top and the sample holder on the bottom. Pumping openings (~10 mm typical dimension) remain on top between the tube and the Al₂O₃ window, and on the bottom between the sample holder and the tube. At this position, the middle of the tube is 5 cm from the bottom of the edge of the reactor’s quartz window (see figure 1) (also from the sample holder’s surface). When the tube is in the lower position, the plasma created between the top antenna and the wafer holder extends towards the stainless steel walls. Most of the characterizations performed in this paper have been performed without the tube. For the purpose of spatial characterization of the plasma, a 4” SiO₂ was loaded on the sample holder and heated to 450 K during measurements. SiO₂ was chosen as a reference material, because of the large number of papers dedicated to atomic hydrogen loss on this material (Kim and Boudart 1991, Kae-Nune et al 1996, Cartry et al 2000, Bousquet et al 2007).

In all cases, the gas flow rate is fixed at 10 sccm. For atomic hydrogen determination by actinometry an admixture of 5% of argon was used in hydrogen. For the determination of the gas temperature 5%, 10%, 15%, 30%, 50% admixtures of nitrogen were used in hydrogen. Signal is collected by an optical fiber through a quartz lens from the chamber. The collected signal is recorded with an Andor Mechelle ME5000 spectrometer coupled with an Andor iStar intensified camera (DH734) in wavelengths ranging from 215–950 nm. Experimental spectra were corrected by the spectral response of the spectrometer. The resolution of the Mechelle spectrometer is $\lambda/\Delta \lambda = 4000$.

Plasma parameters such as electron density and electron temperatures were measured by an RF-compensated SmartSoft Langmuir probe with a tungsten tip 10 mm long and 200 μm in diameter. The Langmuir probe was translatable and was positioned at the center of the plasma chamber at a height of 5 cm from the bottom part of the quartz window.

The transition from CCP to ICP mode is identified and marked for all evolutions shown here. Note that this transition, characterized by a hysteresis effect, occurred with a sudden change of both the emission intensity and plasma density and it was triggered by changing the delivered power.

3. Results and discussion

3.1. Electron density and electron temperature

Measured data with the Langmuir probe (placed in the center of the chamber/plasma, height: 5 cm from the window’s lower part) were processed by software SmartSoftV5.01 from Scientific Systems (Hopkins 1995). The electron temperature and electron density were determined with the help of the
plasma potential, obtained using the zero second derivatives. Figure 2 depicts the measured electron densities in pure H\textsubscript{2} as a function of power and pressure. Overall, the electron densities increase with an increase in the power in the measured range of pressure, i.e., between 1–10 Pa. The transition to the ICP mode is characterized by a sudden jump in the electron densities above \(\sim 10^{10}\) cm\(^{-3}\). With increasing pressure, this transition occurs at lower power values. The mentioned hysteresis effect (Daltrini et al. 2008, Kang and Gaboriau 2011) is evidenced, for example, at 4 Pa and 600 W and the discharge can be both in ICP and CCP mode.

Figure 3 presents the electron concentrations in the case of a H\textsubscript{2}-N\textsubscript{2} plasma at the two pressure limit conditions, at 1 (a) and 10 Pa (b). We recall that the admixture of nitrogen was realized in order to help determine the gas temperature. However, this affected the discharge properties and led to some changes in the electron concentration compared to the case of pure hydrogen. First of all, the H\textsubscript{2}-N\textsubscript{2} plasma is also characterized by rising values of \(n_e\) with both pressure and power as in pure hydrogen and by a sudden increase in \(n_e\) concerning the transition from the CCP to ICP mode. However, at 1 Pa nitrogen causes an important increase in the electron concentrations and even the transition to the ICP mode at 1000 W and 50% N\textsubscript{2} unlike in the case of pure H\textsubscript{2}. An increase in electron density with nitrogen density was observed before and explained by a higher ionization cross-section of N\textsubscript{2} in comparison with H\textsubscript{2} (El-Brusly et al. 2012). In contrast, at 10 Pa approximately the same trend is observed for all dependences as in pure hydrogen, i.e. no important changes are induced with nitrogen addition.

The electron energy distribution function (EEDF) in pure H\textsubscript{2} plasma is depicted in figure 4 for different power and pressure conditions. Note, that there were no important changes with power or plasma mode concerning the shape of the EEDF. Maxwellian EEDF was obtained for lower pressure and it was changed to bi-Maxwellian for pressures higher than 4 Pa. The electron temperatures marked in the graph are merely informative. With decreasing pressure, we see an increase in the high electron energy tail to the disadvantage of the lower energy part. In hydrogen, the transition with pressure from a Maxwellian to a bi-Maxwellian EEDF has been studied previously in a 13.56 MHz CCP discharge (Abdel-Fattah and Sugai 2013) and a bi-Maxwellian distribution was reported at 10 Pa in a pulsed CCP discharge (Osiac et al. 2007).

Measured EEDF was used for the calculation of rate constants used in actinometry (paragraph 3.4) and in the calculation of vibrational temperature (paragraph 3.3).

### 3.2. Gas temperature

As rotational-translational relaxation is non-adiabatic, fast equilibrium can occur between rotational and translational degrees of freedom after a few collisions (Britun et al. 2007). For this reason, the rotational temperature of the ground states of molecules is very often taken as gas temperature. One of the most known emission systems of hydrogen discharge in the visible range is the Fulcher-\(\alpha\) system \((\text{H}_2(\text{d}^3\text{P}_{\text{u}}^0 \rightarrow \text{a}^3\Sigma_{\text{g}}^+)\). For gas temperature determination, often the Q-branch of this system is used as other branches, P and R, are perturbed by \(\Sigma\) states (Qing et al. 1996). The rotational temperature of the \(\text{H}_2(\text{d}^3\text{P}_{\text{u}}^0)\) state determined from the hydrogen Fulcher-\(\alpha\) band is not very often in equilibrium with gas temperature at low pressure, because of the very short lifetime of the \(\text{H}_2(\text{d}^3\text{P}_{\text{u}}^0)\) state. So \(\text{H}_2(\text{d}^3\text{P}_{\text{u}}^0)\) cannot be thermalized. Furthermore, hydrogen needs approximately 300 collisions to achieve equilibrium (Farley et al. 2011) while 5–10 collisions are required for nitrogen. According to Tomassini et al. (1996), the collision frequency as a function of the pressure is given by:

\[
\nu_{\text{coll}}/\text{p} = 8 \times 10^8 \text{s}^{-1}\text{Torr}^{-1}.
\]

The emission probability of the \(\text{H}_2(\text{d}^3\text{P}_{\text{u}}^0)\) band can be used instead of the energy difference between the states in question, i.e.

\[
|I| \propto (2I_{\text{N}^-} + 1)S_{\text{N}^+N^-} \exp \left(-\frac{E_{\text{rot}}/N - \text{hc}}{kT_{\text{rot}}}\right).
\]

where \(S_{\text{N}^+N^-} = \frac{2N^+ + 1}{2}\) is the Hönig–London factor, \(T_{\text{rot}}\) is the rotational temperature of the state and \(E_{\text{rot}}/N = B_{\text{N}}(N + 1)\) is the rotational energy. The total nuclear spin due to the presence of ortho- \((I_{\text{N}^+} = 1)\) and para-states \((I_{\text{N}^-} = 0)\) of H\textsubscript{2} is taken into
account, where $\Gamma_{N'} = 1$ for $N'$ even and $\Gamma_{N'} = 0$ for $N'$ odd. The rotational temperature of $H_2(d^3\Pi_g)$ is then determined assuming a Boltzmann distribution of the rotational states. The rotational constant of $H_2(X^1\Sigma_g^+)$ has to be used for the calculation (since the rotational distribution of the excited state is a copy of the ground state one). However, as the rotational constant of $H_2(X^1\Sigma_g^+)$, $B_{\text{rot}}$, is twice as high as the rotational constant $B_e$ of the $H_2(d^3\Pi_g)$ state ($B_{\text{rot}} = 2B_e$), then it simply applies: $T_{\text{rot}}(H_2(X^1\Sigma_g^+)) = 2T_{\text{rot}}(H_2(d^3\Pi_g))$. For the rotational constant we can write: $B_e = R_e - \alpha_e \left( \frac{1}{2^2} \right)$ with $R_e = 30.364 \text{ cm}^{-1}$, $\alpha_e = 1.545 \text{ cm}^{-1}$ for the $H_2(d^3\Pi_g)$ state and $B_{\text{rot}} = 60.809 \text{ cm}^{-1}$ $\alpha_e = 2.993 \text{ cm}^{-1}$ for the $H_2(X^1\Sigma_g^+)$ state (Herzberg 1955). An example is illustrated in figure 5 for the vibrational transition $\nu' - \nu'' = 1-1$ of the Q-branch of the Fulcher-\(\alpha\) band.

It was observed by Fantz (2002) and also by Tsankov et al. (2012) that temperatures determined from different diagonal bands are not equal. This observation is not yet explained. Fantz compared different spectroscopic techniques and she found out that temperature determined by vibrational bands 1-1 and 2-2 are the closest to the real gas temperature. For this reason, we concentrated on these bands. We have chosen the transition 1-1 (at $\lambda = 612$–616 nm) because of the higher intensity of the rotational lines compared to the vibrational band 2-2. Note that the experimental error in the determination of the rotational temperatures is $\pm 50$ K, coming from the accuracy of the fit. It means that the error for the gas temperature from the Fulcher-\(\alpha\) system is $\pm 100$ K. The determined gas temperatures in pure hydrogen are depicted in figure 6(a). The gas temperature in the CCP mode was equal to an average value of 450 $\pm 50$ K and did not depend on the pressure or delivered power. It is a non-
heating mode where a large proportion of the energy goes into accelerating the ions in the plasma sheath and is not used to heat the gas through electron collisions. On the other hand, the ICP mode can be characterized by collisional heating. In this so-called heating mode the gas temperature increased, because more energy was transferred to the plasma with an increase in the power and with pressure, and the plasma density increased leading to more frequent collisions and larger energy transfer from the electrons to neutral gas. The gas temperature increased with the highest slope at 10 Pa from 525 (400 W) to 800 K (1000 W). Similar values were obtained recently in a high-density low-pressure hydrogen discharge (Samuell and Corr 2015).

In the case of the nitrogen admixture, we compared the gas temperatures determined by the Fulcher-α system and the second positive system of nitrogen \(N_2(C^3\Pi_u \rightarrow B^3\Pi_g)\), denoted as 2PS. We suppose that the rotational temperature of 2PS is equal to the gas temperature (Behringer 1991, Fantz 2004). In the latter case, the vibrational transition \(v' - v'' = 1 - 0\) (at \(\lambda = 315.8\) nm) was used, being the most intense one in the spectra after the transition 0-0, which, however, overlapped with the \(NH(A^2\Pi - X^2\Sigma)\) system. By spectral simulations using the software SPEC Air (Laux 2002) we determined the rotational temperature of the \(N_2(C^3\Pi_u)\) state, which can be considered as the gas temperature with an error of \(\pm 50\) K. The Fulcher-α system could be used for the determination of \(T_g\) only at 5%, 10% and 15% of nitrogen added, as at higher percentages of \(N_2\) (30% and 50%) the first positive system of nitrogen \(N_2(B^3\Pi_g \rightarrow A^3\Sigma_u^+))\) overlapped with the bands from Fulcher-α. Concerning the pressure dependence of the gas temperature in the case of nitrogen admixtures, the behavior is equivalent to that in pure hydrogen. Therefore, figure 6(b) presents the results as a function of power and nitrogen percentage in the mixture only in the case of the pressure of 10 Pa. First of all, the results using 2PS and the Fulcher-α system are in quite good agreement. Even if the error bar is quite large, it reinforces the confidence in the gas temperature determination from the Fulcher-α system. There is only one noticeable difference between the gas temperatures determined from both systems: at 10 Pa and 1000 W the second positive system gives a temperature lower than the Fulcher system. The discharge was in the ICP mode for powers higher than 400 W under the presence of the nitrogen admixture. At 400 W, discharge can be in the ICP and CCP mode in pure hydrogen and also with 5% nitrogen. The transition causes additional heating of the gas as stated before. Thus, for \(H_2-N_2\) mixtures higher gas temperature values were also determined in the ICP mode. For a given power the gas temperature changes with the nitrogen admixture seem to be related to the uncertainty in the measurements rather than to a real change of the heating mechanism. On average, in the ICP mode the gas temperature in mixtures is close to the value determined in pure hydrogen discharge. In the CCP mode with \(N_2\) admixture \(T_g\) was equal to the value determined for pure hydrogen within the determination uncertainty (see the case of 400 W).

For determination of the reflection coefficient of atomic hydrogen, it is possible to use pulsed-discharge and measure the atomic decay in time afterglow. As the gas temperature can influence the decay of atomic hydrogen, we have performed time-resolved measurements of the gas temperature during pulsed plasmas. A duty ratio of ON:OFF = 50 ms:
50 ms was used for investigation of the temporal evolution of the gas temperature. The \( T_g \) values were determined by 2PS and Fulcher-\( \alpha \) systems, as described above and using the transitions mentioned previously. In the pulsed regime, for a gas mixture with 50% nitrogen the Fulcher-\( \alpha \) system was not influenced by the first positive system of nitrogen and could also be used. The results are presented in figure 7 for two measured pressure conditions. The temperature is increasing during the pulse and reaches a stationary value after \( \sim 1.5 \) ms, which corresponds to the value of \( T_g \) in the continuous discharge.

At that time, the value of \( T_g \) in the continuous discharge is achieved. Note that the 2PS at 10 Pa and 1000 W gives a temperature noticeably lower that the Fulcher system, as already observed in the continuous mode. It is not possible to determine the gas temperature during the OFF phase, because of the short lifetime of the excited states.

The reflection coefficient can also be strongly influenced by the temperature of the sample, which can in turn also change the gas temperature. At low pressures the gas particles collide with the surfaces of the chamber much more often than between each other and their loss depends on the surface temperature. The spatial variation of the gas temperature towards the sample was measured both with and without the Pyrex tube at 1000 W and at pressures of 4 and 10 Pa while the sample was heated to 450 K or maintained at 300 K by liquid cooling. If the temperature of the sample is changed, the gas temperature will be changed according to the difference in the sample temperatures. This is in agreement with figures 8(a) and (b), which present the evolution of the gas temperature at 4 and 10 Pa, respectively, with and without the Pyrex tube and at different sample temperatures. For the determination of \( T_g \) the same transition of the Fulcher-\( \alpha \) system was used as in the cases above. The change in the sample temperature to about 150 K changed the gas temperature approximately from 650–800 K at 4 Pa (without tube) and from 800–950 K at 10 Pa (without tube). The Pyrex tube delimited the chamber and also the discharge to smaller dimension. Thus, the power density was higher. This induced higher gas temperature when the Pyrex tube was used. The difference between \( T_g \) with and without the Pyrex tube is lower at 10 Pa, because plasma was not that spatially extended at higher pressure without the tube.

### 3.3. Vibrational temperature of the ground state \( \text{H}_2 \left( ^1\Sigma_g^+ \right) \) and relative negative ion densities

Knowledge about the vibrational population of the ground-state hydrogen, \( \text{H}_2 \left( ^1\Sigma_g^+ \right) \), is important because it can give us information about the production of negative ions, \( \text{H}^- \). The main channel of the creation of \( \text{H}^- \) atoms is usually dissociative attachment of vibrationally excited \( \text{H}_2 \) molecules (Hjartarson et al. 2010, Bacal and Wada 2015). It was shown that there is a correlation between the evolution of the vibrational temperature of the ground state and the concentration of \( \text{H}^- \) species (Kado et al. 2005, Wang et al. 2008). In the following, we describe the method used for the determination of the vibrational temperature. It is based on the investigation of the vibrational distribution of the \( \text{H}_2 \left( ^3\Pi_g \right) \) state. This method is sensitive to the first five vibrational levels as higher levels are populated by the collisional radiative redistribution via the \( \text{H}_2 \left( C^1\Pi_u^+ \right) \) and \( \text{H}_2 \left( B^1\Sigma_u^+ \right) \) states (Hiskes et al. 1985). Vibrational distribution of the \( \text{H}_2 \left( ^3\Pi_g \right) \) state can be calculated according to the Franck–Condon principle (Fantz and Heger 1998, Wang et al. 2008) or by the Gryzinski theory (Xiao et al. 2004). In general, for the determination of ro-vibrational distributions in hydrogen plasmas at low pressures we can use the simple model of corona equilibrium, based on the assumption that the
$H_2(d^3Π_u)$ state is populated primarily by electron impact from the ground state $H_2(X^3Σ^+_g)$ and its de-excitation is caused mainly by radiative transition to the $H_2(a^3Σ^+_g)$ excited state. The rotational and vibrational states of $H_2(X^3Σ^+_g)$ are assumed to present Boltzmann distributions in this method. At steady state the total production and destruction rates according to the mentioned processes of the ro-vibrationally excited $H_2(d^3Π_u)$ state are equal and we can write the following kinetic equation

$$\sum_v (K_{Xv}^{dv} N_{Xv}) = N_{dv} / A_{\text{tot}},$$

where $K_{Xv}^{dv}$ is the electron excitation rate constant from ground state $H_2(X^3Σ^+_g)$ to $H_2(a^3Σ^+_g)$, $N_{Xv}$, $N_{dv}$ are concentrations of the corresponding vibrationally excited states and $A_{\text{tot}}$ is the sum of the transition probabilities from the $H_2(d^3Π_u)$ state to $H_2(a^3Σ^+_g)$ for the rotational, vibrational and electric part. According to Wang et al. (2008) and Fantz and Heger (1998), vibrational distribution of the $H_2(d^3Π_u)$ state can be calculated considering the Franck–Condon approximation

$$N_{dv} \propto \sum_v \alpha_{Xv}^{dv} N_{Xv} \exp(-\Delta G_{vib}/kT_e),$$

where the electron impact excitation rate for the transition $H_2(X^3Σ^+_g) \rightarrow d^3Π_u$ from the ground state with population $N_{Xv}$, is considered to be proportional to the Franck–Condon factors, $\alpha_{Xv}^{dv}$ (Fantz and Wünnerlich 2004), multiplied by an exponential factor which takes into account the threshold of vibrational levels of the ground state, $\Delta G_{vib} = G_v - G_0$, $G_v$ and $G_0$ (Fantz and Wünnerlich 2004) are the energies of vibrational states $v$ and $v = 0$. Finally, $T_e$ denotes the electron temperature. However, Xiao et al. (2004) called upon the fact that the electron impact excitation does not necessarily obey the Franck–Condon principle, particularly for electron temperatures lower than 10 eV. They calculated vibrational distribution according to the following relation

$$N_{dv} \propto \sum_v \alpha_{Xv}^{dv} N_{Xv} \exp(-G_v/kT_e),$$

where $\alpha_{Xv}^{dv}$ is the rate constant for electron impact excitation from the ground state to $H_2(d^3Π_u)$ calculated by the Gryzinski semi-classical theory through the determination of the differential excitation cross-sections (Bauer and Bartky 1965). If we suppose Boltzmann distribution of vibrational states $H_2(X^3Σ^+_g)$, the following will be valid

$$N_{Xv} = \frac{\exp(-G_v/kT_{vib})}{\sum_v \exp(-G_v/kT_{vib})},$$

where $T_{vib}$ denotes the vibrational temperature of the ground-state molecule. Figure 9 presents the calculated population ratios of $H_2(d^3Π_u)$, $v = 0$ and 1 as a function of the electron and vibrational temperature using the Franck–Condon approximation (a) and the Gryzinski theory (b), according to (3) and (4), respectively. The latter presents a maximum, which tends to get sharper for decreasing values of $T_e$. As under our conditions the electron temperatures are lower than 10 eV at lower pressure and bi-Maxwellian at higher pressure, the choice of the method is crucial. Due to the low electron temperature measured in our plasma (much below 10 eV), we have chosen to use the method including the Gryzinski theory, as in Xiao et al. (2004), to calculate the rate constants in order to describe the vibrational distribution of the $H_2(d^3Π_u)$ state.

Concerning the concentration of rotational state $N_{dv/N'}$, we can write

$$N_{dv/N'} = \frac{N_{dv} (2N' + 1)(2N + 1)}{\sum_{N'} \exp(-F_{dv/N'}/kT_{rot})} \exp\left(-\frac{F_{dv/N'}}{kT_{rot}}\right).$$

Figure 8. Evolution of the gas temperature at 4 Pa (a) and 10 Pa (b) with (empty symbols) and without the Pyrex tube (full symbols). The points marked by stars are measured without the Pyrex tube and heating of the sample to 300 K. Other measurements are done at 450 K of the sample holder. The Pyrex tube delimited the chamber and also the discharge to smaller dimensions, increasing the power density resulting in higher gas temperature.
The intensity of rotational line $I_{v' = 0}^{v''}$ of the Fulcher-α band can be expressed as

$$I_{v' = 0}^{v''} = \frac{64\pi^4}{3\hbar \lambda^3} \frac{1}{2N'' + 1} N_{v''} A_{v''}^{v''},$$

where

$$A_{v''}^{v''} = S_{v''}^{d''} q_{v''}^{d''} A_d^{d''},$$

where $S_{v''}^{d''}$ is the rotational line strength or Hönl–London factor, $q_{v''}^{d''}$ the Franck–Condon factors of the transition $H_2(d^3\Pi_u^+ \rightarrow g^3\Sigma_g^+)$ (Fantz and Wunderlich 2004) and $A_d^{d''}$ is the probability of the electronic transition. The intensity can be simplified to

$$I_{v' = 0}^{v''} \propto \frac{1}{\lambda^3} q_{v''}^{d''} N_{v''}.$$  (9)

Then, we obtain for the intensity of the Fulcher-α band lines

$$I_{v' = 0}^{v''} \propto \frac{1}{\lambda^3} q_{v''}^{d''} (2N'' + 1) (2N' + 1) \sum_v \exp \left( -\frac{E_v^{d''}}{kT_{rot}} \right) \times \exp \left( -\frac{F_v^{d''}}{kT_{rot}} \right) \sum_i \frac{\exp \left( -\frac{G_i}{kT_{vib}} \right)}{\sum_i \exp \left( -\frac{G_i}{kT_{vib}} \right)}.$$  (10)

To calculate vibrational temperature of $H_2(X^3\Sigma_g^+, v)$ using equation (10), we used the ratio of rotational lines Q1 from 0-0 and 1-1 bands of $H_2(d^3\Pi_u^+ , v')$ and the rotational temperature $T_{rot}$ of the corresponding vibrational band of the $H_2(d^3\Pi_u^+ , v')$ state was used as the input parameter.
The average vibrational temperature of $H_2(X^3Σ^+_g, ν)$ is 3100 and 2000 ± 500 K in the ICP and CCP mode, respectively.

Within the given uncertainties, the value of the vibrational temperature of the ground state in the spatial direction can be considered constant. At 4 Pa, 1000 W and sample temperature 450 K the average value is equal to 3500 and 4100 ± 500 K without and with the Pyrex tube, respectively, and at higher pressure (10 Pa, 1000 W and sample temperature 450 K) the averaged vibrational temperature is equal to 3700 and 3300 ± 500 K without and with the Pyrex tube, respectively.

Without a complete kinetic modeling of the hydrogen discharge, it is hard to comment on the changes of the vibrational temperature with power, distance from the sample or the presence of the Pyrex tube. Indeed, many parameters play a role in the population/depopulation of the $H_2$ vibrational states, and still some of them are not well documented. For instance, it is known that the vibrational population of $H_2(X^3Σ^+_g, ν)$ can be influenced by surface recombination of atomic hydrogen that creates vibrationally excited molecules (Cacciatore and Rutigliano 2006, 2009), but the exact amount of energy going into the vibration depends on the surface material itself (Fantz 2002), and is usually not known. Wall deactivated vibrationally excited molecules are also a subject of research about which very little is known (Marinov et al 2012, 2014b, Samuell 2014). Vibrationally excited states are also populated by electron impact and V-V transfers, and depopulated by V-V transfers and V-T transfers with H atoms. Finally, the vibrational population might also be affected by ion-molecule collisions (Xiao et al 2005). Many models and studies have been dedicated to the vibrational temperature of $H_2$, taking into account some of the mechanisms described above (Gorse et al 1987, Shakhatov et al 2005, Xiao et al 2005, Mendez et al 2006, Hjartarson et al 2010). Let us note that according to Fantz et al (2001) electron density has an influence on vibrational distribution for electron temperatures higher than 4 eV and electron densities of at least $10^{11}$ cm$^{-3}$. In our study, we obtained lower values for ne and Te. Therefore, we can expect an effect of the wall material when the Pyrex tube is introduced and the vibrational temperature is decreased to 4 Pa.

Kalache et al (2004) found out that the concentration of negative ions is negligible for vibrational temperatures lower than 3000 K. For temperatures higher than 3000 K, the concentration of negative ions increases exponentially. Kimura and Kasugai (2010) supposed the creation of negative ions by dissociative attachment from the vibrationally excited hydrogen molecules of $H_2(X^3Σ^+_g, ν)$ with $ν \geq 4$ and their destruction by detachment collision with atomic hydrogen. They characterized the concentration of negative ions by electronegativity, $α$:

$$α = C_{ad} \frac{[H_2(ν \geq 4)]}{[H]},$$  (11)

where $C_{ad}$ is the ratio of the rate coefficient for the dissociative attachment to that for the detachment, estimated to be around ten at maximum (Janev et al 1987, Graham 1995, Zorat et al 2000). H is the concentration of hydrogen atoms and is obtained from actinometry (see section 3.4.3.).

Figure 11. Calculated $α$ coefficient for various determined vibrational temperatures of ground state $H_2(X^3Σ^+_g)$ as a function of pressure at 400 W (CCP mode) and 1000 W (ICP mode). From the given low values we can assume that the concentration of negative ions is negligible in the CCP mode.

### 3.4. Estimation of concentration of atomic hydrogen

We used two actinometric schemes to determine the H atom concentrations by employing either argon or $H_2$ molecules as an actinometer. First, we discuss the theory behind the two studies (see sections 3.4.1. and 3.4.2.), and then we present the results (see section 3.4.3.).

#### 3.4.1. Actinometric study with argon admixture

We used 5% argon as an actinometer. The basic assumption is that this amount will not significantly change the discharge properties. The following processes were taken into consideration, where $i$ and $j$ refer to electronic excited states.

- Direct excitation from the atomic ground state (IST-Lisbon database):
  $$H + e \xrightarrow{k_i^H} H_i + e \text{ with } σ_{e}^{H}(E)$$  (12)
  $$Ar + e \xrightarrow{k_{Ar}^j} Ar_i + e \text{ with } σ_{e}^{Ar}(E).$$  (13)

- Dissociative excitation (IST-Lisbon database):
  $$H_2 + e \xrightarrow{k_d^H} H_i + H + e \text{ with } σ_{d}^{H}(E).$$  (14)

- Radiative decay (Physical Meas. Laboratory NIST database):
  $$H_i \xrightarrow{A_i^H} H_i + hν_i^H \text{ with } A_i^H$$  (15)
Assuming that any other mechanism has only a negligible contribution to the population/depopulation of excited states, we can write at steady state:

$$I_H = \frac{\lambda_{ij}^{(N)} A_{ij}^{(N)} (k_H^i [H] + k_d^i [H_2]) \sum_{k<j} \lambda_{ik}^{(N)} A_{ik}^{(N)} k_e^i k_d^i [Ar]} {\lambda_{ij}^{(N)} A_{ij}^{(N)} k_e^i [Ar] \sum_{k<j} \lambda_{ik}^{(N)} A_{ik}^{(N)}}.$$  

(17)

We supposed that particles with the highest concentrations are hydrogen molecules and neutral atomic hydrogen. The concentration of hydrogen molecules can be expressed as

$$[H_2] = \frac{p_{off}}{kT_g} - [H] - [Ar].$$  

(18)

The gas temperature $T_g$ is taken from the measurement, $p_{off}$ is neutral gas pressure in the chamber before ignition of discharge given by the capacitance gauge, $[Ar]$ is 0.05$(p_{off}/kT_g)$ and rate constants were calculated using EEDF from paragraph 3.1. In actinometry, two transitions having excitation cross-sections varying in a similar way to electron energy are introduced. Finally, the hydrogen density is given by:

$$[H] = \frac{I_H \lambda_{ij}^{(N)} A_{ij}^{(N)} \sum_{k<j} A_{ik}^{(N)} k_e^i [Ar]} {I_{Ar} \lambda_{ij}^{(N)} A_{ij}^{(N)} \sum_{k<j} A_{ik}^{(N)} (k_e^i - k_d^i)} - \frac{k_d^i}{k_e^i} \left( \frac{p}{kT_g} - [Ar]. \right).$$  

(19)

### 3.4.2. Actinometric study in pure hydrogen.

The rotational line with $N = 1$ of the Q-branch of the Fulcher-α band of vibrational transition $v - v' = 2 - 2$ was used as the actinometric line. In addition to the reactions mentioned before, we took into consideration the following ones:

- **Radiative decay** (Käning et al. 1999):

$$H_2(d, v', N = 1) \xrightarrow{H_2(d,v',N=1)} H_2(a, v'', N) + h\nu_{d-a}^{H_2(d,v',N=1)} [H_2(d, v', 1)].$$  

(21)

Intensity of hydrogen excited state and rotational line $N = 1$ of the Q-branch of the Fulcher-α band is given:

$$I_Q = kT_g \frac{p_{off}}{k} [H] [H_2(X, v = 0, N = 1)],$$  

(22)

where

$$[H_2(d, v', 1)] = k_e^{H_2(d,v',1)} [H_2(X, v = 0, N = 1)] n_e \times \sum_{k<j} A_{ik}^{(d,v',1)}.$$  

(23)

Ratio of atomic hydrogen line and rotational line of the Fulcher-α band will be equal to

$$\frac{I_H}{I_Q} = \frac{\lambda_{ij}^{(N)} A_{ij}^{(N)} (k_H^i [H] + k_d^i [H_2]) \sum_{k<j} \lambda_{ik}^{(N)} A_{ik}^{(N)} k_e^i k_d^i [Ar]} {\lambda_{ij}^{(N)} A_{ij}^{(N)} (k_H^i [H_2(X, v = 0, N = 1)]) \sum_{k<j} A_{ik}^{(d,v',1)}},$$  

(24)

where we can write that

$$[H_2] = \frac{p}{kT_g} - [H].$$  

(25)

and

$$\eta(T_g) = \frac{H_2(X, v = 0, N = 1)}{H_2} = \frac{9}{4} \sum_{N=1}^{3,5,\ldots} (2N + 1) \exp \left( \frac{-E_N}{kT_g} \right),$$  

(26)

where $T_g$ is assumed to be equal to $T_{rot}$ of the ground state of $H_2$. The formula (26) according to Lavrov et al. (2003) describes the influence of rotational excitation on the population of the rotational level $N = 1$. $E_N$ is the energy of the rotational level with the rotational quantum number $N$ in the $v = 0$ ground vibrational state of molecular hydrogen. Finally, it comes as

$$[H] = \frac{I_H \lambda_{ij}^{(N)} A_{ij}^{(d,v',1)} k_e^{H_2(d,v',1)} \sum_{k<j} A_{ik}^{(d,v',1)} k_e^{H_2(d,v',1)} [Ar]} {I_{Q1} \lambda_{ij}^{(N)} A_{ij}^{(N)} \sum_{k<j} A_{ik}^{(N)} \eta(T_g) \frac{p}{kT_g} - k_d^i \frac{p}{kT_g}} - \frac{k_d^i}{k_e^i} \left( \frac{p}{kT_g} - [Ar]. \right).$$  

(27)

where $\sigma_e^{H_2(d,v',1)}(E)$ was calculated from semi-classical theory of Gryzinski and $a_{N,N'}$ from adiabatic approximation (Xiao et al. 2004, Farley et al. 2011).

### 3.4.3. Comparison of results from the two actinometric studies.

Figures 12(a) and (b) present the evolution of the hydrogen atoms concentration with pressure of 400 and
1000 W calculated using argon or H₂ as an actinometer. In the case of argon, the Ar transition from 2\(p_1\) to 1\(s_2\) at 750.4 nm has been used and two different H transitions have been employed: H-alpha line at 656 nm (figure 12(a)) and H-beta line at 486 nm (figure 12(b)). For hydrogen, the Q-branch of the Fulcher-\(\alpha\) band has been used.

First, we can note that the two hydrogen transitions give different results. Actinometry using the H-alpha line results in higher concentrations of atomic hydrogen than using the H-beta line. Similar results were observed by Skoro et al. (2013). They observed better agreement between atomic hydrogen concentrations determined from actinometry and catalytic probe measurements when using the H-beta line rather than H-alpha. Therefore, we have considered the H-beta line for further calculations. We can also see that Fulcher-\(\alpha\) and argon actinometry (H-beta) are in good agreement (figure 12(b)), which is not the case for the results obtained with the H-alpha line (figure 12(a)), confirming that the use of H-alpha should be avoided here. The presented graph shows the evolution of H atom concentrations in the CCP and ICP modes with pressure between 2–10 Pa. In general, the H atom concentration increases with the pressure. Surprisingly, we have obtained a higher H concentration in the CCP mode than the ICP mode, with densities ranging from around 1.5\( \times \)10\(^{13}\) to 7.5\( \times \)10\(^{13}\) cm\(^{-3}\) in CCP and from 1\( \times \)10\(^{13}\) to 4\( \times \)10\(^{13}\) cm\(^{-3}\) in the ICP mode with increasing the pressure from 3–10 Pa. This point is discussed later.

Relative to previous works, comparable values of hydrogen concentration were found by Mendez et al. (2006) in a DC discharge with values between 10\(^{12}\)–10\(^{14}\) cm\(^{-3}\) in a pressure range 1–10 Pa at electron densities between 1–3 \(\times\) 10\(^{16}\) cm\(^{-3}\) and decreasing the electron temperature from 8–2 eV. Marques et al. (2007) measured a value of 7 \(\times\) 10\(^{13}\) cm\(^{-3}\) but at higher pressure, 26 Pa, with the electron density up to 4 \(\times\) 10\(^{9}\) cm\(^{-3}\) and electron temperature of 3 eV in a CCP RF discharge at 13.56 MHz. At lower pressure, 1 Pa, in a helicon-type reactor Skoro et al. (2013) determined a concentration of hydrogen atoms between 5–9 \(\times\) 10\(^{12}\) cm\(^{-3}\) at power ranging between 800–1000 W.

Figure 13 depicts the evolution of the dissociation ratio as a function of pressure at 400 and 1000 W. The dissociation ratio is higher in the ICP mode than the CCP mode.
dissociation). Still, it is surprising that the dissociation degree in the ICP and CCP mode are so close, while the electron density differs by one order of magnitude. This might be due to the increased ion flux to the wall that leads to a higher atomic loss at the wall as observed or suggested in different works (Cartry et al. 1999, Jolly and Booth 2005, Samuell and Corr 2015). Regarding the literature, the obtained dissociation is comparable with results of other works. In the work of Hjartarson et al. (2010) the dissociation was 25% at 0.53 Pa, 20% at 1 Pa and 5% at 13 Pa in pure H\textsubscript{2} discharge. The dissociation ratio decreased from 17%–7% in the pressure range 0.8–20 Pa according to the article of Mendez et al. (2006) combining experimental and theoretical study on a hollow cathode DC discharge.

We also measured the temporal evolution of the H atom concentrations in the pulsed mode. We observed an initial fast increase (shorter than 5 ms), and then the H density reached more or less the value reached in the non-pulsed mode. At the end of the discharge pulse, the H density reaches 1.5 × 10\textsuperscript{13} and 4.5 × 10\textsuperscript{13} cm\textsuperscript{-3} at 4 and 10 Pa, respectively.

Figure 14 presents the evolution of the H atom concentrations as a function of distance from the sample holder at 4 and 10 Pa with delivered power of 1000 W. Argon actinometry with H-beta was used here. We observe higher density with the tube than without. This is due both to the higher power density (discharge volume is smaller with the tube) and to the use of Pyrex as the wall material (rather than stainless steel) allowing us to reduce the atomic loss. Indeed, surface loss on glass materials is usually much lower than on metals, one order of magnitude difference (e.g. for glass: Cartry et al. 2000, Rousseau et al. 2001, Macko et al. 2014). The concentration at 10 Pa is higher than at 4 Pa by a factor between 2.5 and 5. For both pressures there is a slight rise in atomic concentration with increasing distance from the sample holder. It is correlated to the loss of atoms at the sample surface. Loss coefficient can theoretically be determined from the slope. However, the determination is quite hard in the presence of temperature gradients (Booth et al. 2005) as it is in the case in the present study.

4. Conclusion

This study presents a preliminary characterization of a hydrogen plasma source, proposed for the determination of the reflection coefficient for fusion-related studies. Within the framework of this project, a hydrogen RF discharge was studied at a frequency of 13.56 MHz, at pressures between 4–10 Pa, and for power in range the of 400–1000 W. The characterization of the plasma was realized by means of optical emission spectroscopy in both the CCP and ICP discharge modes. Moreover, Langmuir probe measurements were carried out in order to determine the electron energy distribution function and electron density. Some measurements were realized in admixtures of nitrogen up to 50% and actinometry measurements in 5% argon. In addition, for some cases of the studied discharge parameters the analysis of a pulsed discharge with a duty ratio 50:50 has been included. The experimental set-up allowed for the investigation of the plasma in the presence of a sample or in the absence of it. For some measurements a Pyrex tube was used, which delimited the volume of the discharge, allowing for a better definition of the wall conditions for surface loss measurements. Note that the placement of the sample (SiO\textsubscript{2}) within the experimental set-up allowed for the interaction with the plasma, while the sample holder (made of molybdenum) could be heated to a desired temperature.

First of all, the electron densities were observed to be increasing with both pressure and power. The transition to the ICP mode was characterized by a sudden jump in the electron densities above ∼10\textsuperscript{13} cm\textsuperscript{-3}, observed for both pure hydrogen and in a H\textsubscript{2}-N\textsubscript{2} discharge. The energy distribution function of electrons was found to be a Maxwellian one at low pressure, but with increasing pressure it gradually changed to a bi-Maxwellian one at around 4 Pa. There was no power dependence observed.

The gas temperature in the CCP discharge mode was constant with pressure and power with an average value of 450 ± 50 K. In the ICP mode the gas temperature increased with an increase in pressure and power, in accord with the literature. These values were obtained from the Fulcher-α system of hydrogen, but also confirmed by H\textsubscript{2}-N\textsubscript{2} mixtures by the second positive system of nitrogen. For the case of a pulsed discharge, the temperature increased during the pulse and reached a stationary value after ∼1.5 ms, which corresponded to the value of the continuous discharge.

The vibrational temperature of the ground-state H\textsubscript{2}(X\textsuperscript{1}S\textsubscript{0}, ν) molecule was determined using the Gryzinski theory. The corresponding functions were found to be approximately constant with respect to both pressure and power for a given mode, but differ significantly between the CCP and ICP modes. The average vibrational temperature of
$H_2(\chi X\Sigma_g^+, v)$ was 3100 and 2000 ± 500 K in the ICP and CCP mode, respectively. The vibrational temperature was also studied as a function of the distance from the sample.

Based on calculations of the electronegativity, found to be 0.01 in the CCP mode and below 0.4 in the ICP mode, and also referring to previous studies, the concentration of negative ions is assumed to be negligible in the CCP mode.

The atomic hydrogen concentration was determined by actinometry using 5% Ar as a probing gas, or by using the Q1 rotational line of the Fulcher-α system as an actinometer. The concentration of hydrogen density increased with pressure in both modes (from around $1.5 \times 10^{13}$ to $7.5 \times 10^{13} \text{ cm}^{-3}$ in CCP and from $1 \times 10^{13}$ to $4 \times 10^{13} \text{ cm}^{-3}$ in the ICP mode with an increase in pressure from 3–10 Pa), but with a dissociation degree slightly higher (by a factor of 2) in the ICP mode. In the case of a pulsed discharge, an initial fast increase in atomic concentration was observed. Then, at around 5 ms, the value reached the value of the continuous mode.

The presented study will be a starting point for further calculations of reflection coefficient versus experimental conditions. This kind of study requires a good knowledge and good characterization of the plasma for two main reasons. The first concerns the measurement of the loss coefficient that in itself can be badly estimated if effects such as gas temperature and neutral density variations are not well managed (Cartry et al 2006, Lamara et al 2006). Second, a key point in surface loss studies is the identification of the parameters that play a role in the surface loss coefficient. The external control 'knobs' of the plasma (pressure, power...) affect several plasma parameters and several species of concentration at the same time. Unraveling the influence of all plasma parameters on the surface loss coefficient thus requires a complete characterization of the plasma versus the experimental conditions. Using the present experimental device, the ion flux can be varied in a controlled manner, the gas temperature is known and most of the plasma parameters are estimated. This is a pre-requisite for H atomic loss coefficient studies.

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