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H⁻ and D⁻ production efficiency in a multi-dipole ECR-plasma source as a function of gas pressure

M Mitrou^{1,2}, P Svarnas¹ and S. Béchu²

CNRS/IN2P3, Grenoble F-38026, France

¹High Voltage Laboratory, Electrical and Computer Engineering Department, University of Patras, Rion–Patras GR–26504, Greece ²Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble–Alpes,

svarnas@ece.upatras.gr

Abstract. The electron cyclotron resonance (ECR) negative ion source "Prometheus I" is operated either with high purity H_2 (> 99.999%) or D_2 (> 99.8%) to probe H⁻ and D⁻ ions, respectively, and examine the isotope effect within a wide range of gas pressure. These ions are predominantly formed in the bulk plasma by dissociative attachment (DA) of low-energy (cold) electrons to highly ro-vibrationally excited molecules. The latter result mainly from the radiative decay and excitation (EV) process sustained by high-energy (hot) electrons confined in the ECR zones. Langmuir probe and laser photo-detachment measurements are realized within the pressure range 0.27 to 2.67 Pa under constant microwave power (0.9 kW). It is revealed that: (i) the plasma potential, cold electron temperature, and cold electron density tend to be higher in deuterium; (ii) no pronounced difference in the hot electron density and temperature is found between the two plasmas; and (iii) overall a similar H⁻ and D⁻ negative ion yield (up to 6×10^{15} m⁻³; under the present conditions) is achieved. However, for equal plasma densities an isotope effect is exhibited showing higher H⁻ density over the entire pressure range. Finally, the n_{H⁻} / n_e ratio is constantly higher than the n_{D⁻} / n_e one and they both peak around 1.33 Pa.

1. Introduction

The heating and current drive of the ITER plasma will rely on the injection of a total of 33 MW of 1 MeV D^0 . The formation of these powerful D^0 beams will be based on the neutralization of accelerated D^- beams since, at such high energies, the efficiency of this process remains acceptable (at around 56%) for negative ions but becomes unsuitably low for positive ions [1]. Considerable progress has been made at the prototype test facility ELISE, yet still only 66% of the ITER demand for extracted negative ion current density has been reached over a time span of 45 min [2]. Additionally, operation with H₂ is foreseen for the early, non-nuclear phases of ITER.

Thus, any fundamental study on a laboratory scale on a direct comparison between H_2 and D_2 plasma properties would be of added value for the general project of fusion application. Indeed, this task has triggered the interest of different research groups, regardless of the type of source employed. Nevertheless, most of the actual experiments refer to H_2 whereas the final fuel will be D_2 and not adequate number of works have been devoted to a direct comparison of the two plasma under identical conditions. This holds true especially in the case of electron cyclotron resonance (ECR) driven sources. Indicatively, such comparative tests have been realized in an ECR source with driven plasma rings [3], at the laboratory scale experiment HOMER (HOMogeneous Electron cyclotron Resonance plasma) [4, 5], and in the SCHEME source (Source of exCited HydrogEn MolEcules) [6].

Accordingly, the present work is devoted to the ECR volume source Prometheus I, extending its exploitation to D_2 since previously operation only with H_2 had been thoroughly carried out [7, 8]. Basic plasma properties are accessed via electrostatic probe and laser induced photo-detachment. The experiments are carried out throughout a wide range of working pressure, whereas the microwave power is maintained constant. The results are then compared and evaluated so as to identify similarities and differences between the ECR plasmas of the two isotopes. The isotope effect is mirrored on the electron energy distribution functions (EEDFs) of the H_2 and D_2 plasmas, and it is also noticeable on the negative ion to electron density ratio. Despite that, comparable H^- and D^- negative ion densities are achieved.

2. Experimental setup

A thorough description of the negative ion source Prometheus I and the details on the diagnostic techniques are given elsewhere [7, 8]. The source is driven by five elementary ECR modules with permanent magnets (875 G) and all measurements are realized at 65 mm downstream of the ECR zones middle planes. Four sets of measurements are conducted, providing mean values and standard deviations (see error bars in figures). Operation within the pressure range of 0.27 to 2.67 Pa (accuracy around $\pm 0.25\%$) may be achieved by the insertion of either H₂ (99.999%; AirLiquide) or D₂ (99.8%; Linde) gas (digitally controlled mass flow). The microwave (2.45 GHz) power is fixed at 0.9 kW in total. Source wall conditioning when the two gases are interchanged requires special attention since notable variations in the plasma properties are observed. This effect can most likely be attributed to the adsorption of remainders of the formerly used gas into the interior surfaces of the source, also known as gas retention. In order to ensure wall recovery, i.e. eliminate this issue and achieve stable and reproducible plasma properties, various trials led to the following protocol: each gas switch is followed by a bake-out of the source at 150°C, under base pressure $(5.33 \times 10^{-5} \text{ Pa})$, for at least 30 h. Throughout the entire experimental series, the temperature of the source walls is not controlled in any manner, therefore it is solely influenced by the operational parameters and the measurement sequence. However, it is monitored using a thermocouple for consistency reasons. In between measurements, a 20-min interval is allowed for the thermal stabilization of the source. Herein, the measurements are conducted in a descending order relative to pressure, i.e from 2.67 Pa to 0.27 Pa (flow rate: 3.9 to 23.4 sccm for H_2 and 4.8 to 29.2 sccm for D₂), during which the temperature of the lateral walls increases from about 89.5 to 118.7 °C and 104.1 to 125.3 °C for H₂ and D₂, respectively. EEDFs are constructed from the probe curves quasi-experimentally, i.e. by fitting a bi-Maxwellian function to the electron current component of the probe curve and its subsequent double derivation (see [8] for details).

3. Results

Fig. 1 clearly shows that two electron populations are produced due to ECR heating, a "cold" and a "hot" one, having about one order of magnitude difference in their temperatures. At the same time, **Fig. 2** gives the absolute density values of these populations. The low-density hot population is a fingerprint of the even more energetic electrons generated in the ECR zones, whereas the high-density cold population refers to the electrons escaping these zones. The former promotes ro-vibrational excitation of molecules (EV reaction), which diffuse away of the ECR zones. The latter promote H⁻ and D⁻ ion production through the dissociative attachment (DA) reaction between them and the diffused excited molecules, in the source volume.

Higher plasma potential (up to about 2 V difference; not shown here), and higher cold electron temperatures and densities are obtained in the case of D_2 over almost the entire pressure range, whereas the isotope effect practically ceases to exist in the case of hot electron temperatures and densities. These observations on the electrons are jointly mirrored on the EEDF patterns depicted in **Fig. 3**. The diverging features between the H_2 and D_2 EEDFs are more pronounced at the lower pressures.



Figure 1: (a) Cold and (b) hot electron temperature vs. the operating gas pressure. • H_2 ; O_2 ; 0.9 kW.



Figure 2: (a) Cold and (b) hot electron density vs. the operating gas pressure. • H_2 ; O_2 ; 0.9 kW.

On the other hand, **Fig. 4(a)** makes a direct comparison between the negative ion yields achieved in the two gases. At a first glance, the H⁻ and D⁻ densities have a qualitatively and quantitatively similar evolution vs. the operating pressure, i.e., a sharp increase is followed by a quasi-saturated phase. Despite that, an obvious isotope effect is exhibited by a different presentation of the data. In **Fig. 4(b)** the relative negative ion density is given, unveiling a strong isotope effect in favour of H₂ and a sharp optimum around 1.33 Pa in both gases. On the top of that, **Fig. 5(a)** compares the H⁻ and D⁻ densities under equal plasma densities (cold electrons), after pressure elimination. Higher values for the H⁻ density, are observed. The corresponding curves versus the hot electrons (**Fig. 5(b**)) are associated with closer experimental points in the two gases.



Figure 3: EEDFs under bi-Maxwellian assumption at (a) 0.27 Pa, (b) 1.33 Pa, and (c) 2.67 Pa. • H_2 ; $\circ D_2$; 0.9 kW.



Figure 4: (a) H⁻ & D⁻ ion density and (b) H⁻ & D⁻ ion to cold electron density ratio vs. the operating gas pressure. • H₂ ; \circ D₂ ; 0.9 kW.

4. Discussion

A rigorous interpretation of the isotope effects recorded here demands the consideration of the production and destruction paths of the H⁻ and D⁻ ions and their molecular precursors $H_2(v)$ and $D_2(v)$. Furthermore, the present data are perfectly linked to the cross sections of many production/destruction processes in H_2 and D_2 [9, 10], but this will be the object of another report. Briefly, the results support EV and DA as dominant production paths. Instead, main destruction paths include vibrational translational relaxation in collisions with atoms (V-t process) or molecules (V-T process) and electron detachment from H⁻ and D⁻ upon their collision with atoms. Atomic and molecular densities increase with higher pressure, affecting the above processes, and an optimum pressure for $H_2(v)$ and H⁻ production has also been observed in other ECR- or filament-driven sources [11].



Figure 5: $H^- \& D^-$ ion density vs. (a) cold and (b) hot electron density. Data pairs are created with the pressure elimination. • H_2 ; $\circ D_2$; 0.9 kW.

5. Conclusions

ECR-driven plasmas led to H⁻ and D⁻ ion production associated with densities within the same order of magnitude (10^9 to 10^{10} cm⁻³) over a wide range of pressure (0.27 to 2.67 Pa). However, an isotope effect was demonstrated with respect to the plasma potential, cold electron temperature and density, all being generally higher in the D₂ case. Additionally, the isotope effect exists for the negative ions too, when they were compared under equal plasma densities, promoting in this case higher H⁻ than D⁻ ion densities. Finally, a distinct optimum of the negative ion to electron density ratio appeared at around 1.33 Pa, yielding a higher peak in the case of H₂ plasma.

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