Physics of Plasmas

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ABSTRACT

Vacuum ultraviolet (VUV) emission diagnostics for studying differences of electron impact processes in hydrogen and deuterium plasmas are presented. The method is applied to study a filament driven multicusp arc discharge negative ion source by comparing the VUV-emission intensities of different emission bands and extracted currents of H^-/D^- ions and electrons. It was found that the ratio of coextracted electrons to extracted ions is four times higher for deuterium than for hydrogen. No significant differences of the VUV-spectra or volumetric rates of ionization, excitation, production of high vibrational states, and dissociation were found between the plasmas of the two isotopes. The volumetric rates of these electron impact processes are presented for both discharges. It is concluded that in the filament ion source, the observed difference of H^-/D^- production through dissociative electron attachment is due to different diffusion rates across the magnetic fields of the tandem-type discharge chamber rather than the production rate of ground state molecules at their vibrational levels.

I. INTRODUCTION

Negative hydrogen (H^-) and deuterium (D^-) ion sources are used as injectors for particle accelerators and neutral beam heating in magnetic confinement fusion research. In particle accelerators, the use of negative ions enables the efficient charge exchange ($H^- \rightarrow H^+$)[1] injection or the extraction of the ion beam, e.g., into storage rings or from circular accelerators, respectively. Meanwhile, the primary plasma heating method in several magnetic confinement fusion experiments is the injection of an energetic beam of neutral hydrogen or deuterium atoms. The most efficient technique to produce neutral beams in the energy range required by recent and future experiments is neutralizing negative ion beams by stripping the additional electron in collisions with the background gas.[2]

The production of the negative hydrogen ions occurs via two main processes (Ref. 3 and references therein). Negative ions are formed in the plasma volume by the attachment of a cold electron to a rovibrationally excited hydrogen molecule, which then dissociates into H^- and neutral H. Along with the volume production by dissociative electron attachment (DEA), the highest performance ion sources also utilize the surface production of negative hydrogen ions. The surface production occurs as a result of an interaction between the hydrogen plasma (atoms, molecules, and ions) and a low work function surface facing the plasma. The work function of the conversion surface is typically lowered by a thin layer of caesium achieved by seeding caesium into the plasma volume.

Most of the negative hydrogen ion sources are based on the so-called tandem design[4,5] where the plasma volume is divided into two regions by a dipole (transverse) magnetic field, often referred as the magnetic filter. The plasma heating occurs in the driver region where electrons are heated by utilizing biased hot cathodes or electromagnetic fields at RF/microwave frequencies (from megahertz to gigahertz). In the driver region, a certain fraction of the electrons have enough energy ($E_e > 10$ eV) to ionize and/or electronically excite neutral hydrogen atoms and molecules. Some of the molecular excitations lead to high rovibrational levels of the ground state molecules or molecular dissociation, which are key elements for the production of negative hydrogen ions. The filter field enhances the production of negative ions by limiting the diffusion of high energy electrons from the driver region toward the plasma electrode and extraction, which results in lower electron temperature enhancing the production and

survival probability of negative ions.[5] The negative ions are directly extracted from the filter field, which reduces the current of coextracted electrons regardless of the primary ionization mechanism, i.e., volume or surface production.

Hydrogen and deuterium differ from each other only by their nuclear structure, i.e., the hydrogen nucleus is a single proton, whereas the deuterium nucleus is composed of a proton and a neutron. Since the electrical properties (number of electrons) of the two isotopes are similar, it could be assumed that the nuclear composition does not significantly affect the plasma properties and reaction rates of low temperature plasmas. However, the deuterium atom is twice as massive as the hydrogen atom, which affects the relevant processes at the quantum level and the plasma kinematics. For example, the rotational-vibrational motions of hydrogen and deuterium differ drastically, which leads to significant differences in the cross sections of electron impact excitation to repulsive triplet states and dissociative electron attachment.[6] Furthermore, the mass difference between hydrogen and deuterium affects their drift velocities and gyroradii in magnetic fields. Because the inverse reactions of several plasma chemical processes occur on the surface of the plasma chamber and magnetic fields play a key role in the ion source design, such differences between hydrogen and deuterium could significantly affect the plasma dynamics.

It has been found that the performance of both pure volume and surface enhanced negative ion sources is lower when deuterium is used instead of hydrogen (see, e.g., Refs. 7–9 and references therein). In particular, the electron to negative ion ratio of the extracted beam is notably higher in the case of deuterium. The high fraction of coextracted electrons is especially problematic for the development of deuterium ion sources for neutral beam injection.[8] The physical processes causing the observed difference are not fully understood, and thus, there is a constant demand for experimental methods, which could identify or exclude reasons for the performance difference from the plasma dynamics point-of-view.

The main motivation for this study is to provide tools for studying the differences in plasma heating power dissipation between hydrogen and deuterium plasmas by using Vacuum ultraviolet (VUV)-emission spectroscopy. Quantifying the VUV-emission allows straightforward diagnostics of different inelastic electron impact processes for which the reaction rates would be challenging to derive, for example, from Langmuir-probe measurements. The rates of the electronic transitions emitting photons in the VUV-range are directly proportional to the rates of ionization and excitation of high vibrational levels through electronic excitations, which are the key ingredients for negative ion production via dissociative electron attachment (DEA). The diagnostics were originally presented for hydrogen in Refs. 10 and 11 and applied to a filament driven arc discharge. Here, we elaborate on the previous study by presenting a detailed comparison of the diagnostics applied to hydrogen and deuterium plasmas. In addition to vacuum ultraviolet (VUV) emission spectroscopy of the driver region, the effect of the biased plasma electrode voltage on the extracted currents of negative ions and electrons is used as a diagnostics for the phenomena occurring in the extraction region. In Sec. II, the isotope effects relevant for the diagnostics are first considered from a theoretical point of view, followed by experimental results in Sec. IV. It is demonstrated hereafter that the lower performance of the ion source in terms of extracted negative ion current of deuterium cannot be explained by the first step of the DEA process, i.e., the production rate of high vibrational levels of ground state molecules in the driver-region (probed by the VUV emission rate), but can more likely be attributed to an isotopic effect in the plasma diffusion rate across the magnetic filter field.

II. THEORETICAL BACKGROUND

The principles of the VUV-diagnostic of hydrogen molecule electron impact processes were first presented in Refs. 10 and 11. The method is based on the detection of two hydrogen molecule emission bands in the vacuum ultraviolet (VUV) range: Lyman-band emission at 150–165 nm and molecular continuum emission at 180–220 nm. The Lyman-band photons are emitted by the lowest singlet transition ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$), while the molecular continuum photons originate from the two lowest triplet transition ($a^3\Sigma_g^+ \rightarrow b^3\Sigma_u^+$). The analysis of these emission ranges is straightforward as there is no significant overlap with neighboring emission bands. However, a minority (9%–15%) of the molecules in the $B^1\Sigma_u^+$ state are populated by a cascade from the $EF^1\Sigma_g^+$ state, which is taken into account in the analysis.

The functional shapes (energy dependence) of the electron impact excitation cross sections follow the transition rules of the electronic transitions.[12,13] The cross sections of the optically allowed singlet excitations have a broad energy dependence, whereas the cross sections of the optically forbidden triplet excitations peak near the threshold energy as demonstrated in Fig. 1. Furthermore, the functional shape of the electron impact ionization cross section is similar to those of the singlet state excitations.

The applied diagnostic method is based on the comparison of the reaction rates of certain chemical processes and those of electronic excitations emitting photons in the VUV-range. The volumetric rate R of an electron impact process can be described as

$$R = n_e n_n \int f(v) v \sigma(v) dv = n_e n_n \langle \sigma v \rangle, \quad (1)$$

where n_e is the electron density, n_n the neutral molecule density, f normalized electron velocity distribution function (EVDF), v the electron velocity, and σ the cross section of the process. The term $\langle \sigma v \rangle$ is the

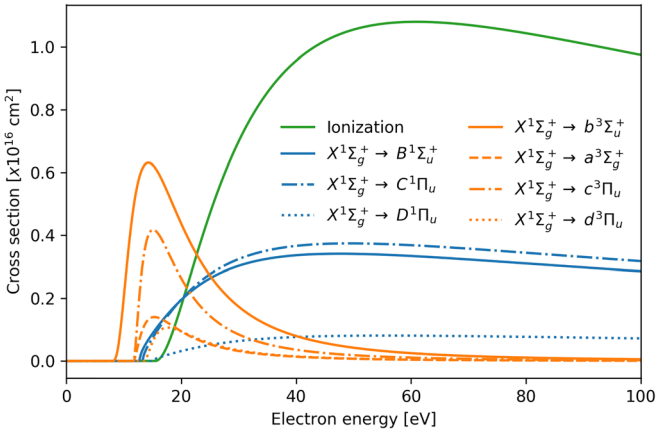

FIG. 1. Electron impact cross sections for the most significant inelastic collision processes of hydrogen molecules at electron energies above 10 eV. Ionization, singlet excitation, and triplet excitation cross sections are marked with green, blue and orange colors, respectively. The cross sections are from Ref. 12.

rate coefficient, which depends on the EVDF and the cross section. In molecular plasmas, the volumetric rate of a given electron impact process depends on the vibrational distribution of the molecules. The total volumetric rate can be calculated as a weighted average of the rate coefficients corresponding to individual vibrational levels. For a Boltzmann distribution of vibrational levels, the result can be written as

$$R(T_{vib}) = n_e n_n \frac{\sum_i \langle \sigma v \rangle_i \exp\left(-\frac{E_i}{kT_{vib}}\right)}{\sum_i \exp\left(-\frac{E_i}{kT_{vib}}\right)} = n_e n_n \alpha(T_{vib}), \quad (2)$$

where T_{vib} is the vibrational temperature, E_i is the energy of the vibrational level i of the ground state molecule, and $\langle \sigma v \rangle_i$ is the total excitation rate coefficient from the ground state vibrational level i to all possible vibrational levels of the upper electronic state. If the volumetric rate of a specific process (R_1) can be determined, e.g., by measuring the volumetric emission rate of a specific band of VUV emission, the volumetric rate of another process (R_2) can be estimated from the ratio of the rate coefficients

$$\frac{R_1}{R_2} = \frac{n_e n_n \alpha_1(T_{vib})}{n_e n_n \alpha_2(T_{vib})}. \quad (3)$$

When the functional shapes of the electron impact cross sections for these two processes are similar, the ratio of the rate coefficients is almost independent of the plasma parameters. In other words, the measurable photon emission rate is linearly proportional to the corresponding plasma chemical process such as molecular ionization or dissociation, which cannot be detected directly. The diagnostics method has been concluded to be valid, when the molecular plasma is in corona equilibrium, i.e., the plasma density is below $10^{16}\,\mathrm{cm}^{-3}$, the neutral gas pressure is below 500 Pa, and the electron temperature is equal or higher than the ion temperature.[11] These conditions prevail in the driver regions of hydrogen ion sources from where the majority of the VUV-light is emitted. The most relevant plasma chemical processes in negative hydrogen ion sources are ionization, vibrational excitation of the ground state molecules, and molecule dissociation. The volumetric rates of certain reaction channels of these processes can be estimated with the described VUV diagnostics.

The short-lived electronic excitations emitting in the Lyman- and Werner-bands lead to high vibrational levels of the ground state molecule due to the Franck-Condon principle.[5,14] A fraction of these excitations also lead to molecule dissociation via the vibrational continuum of the ground state.[15] Furthermore, the electron impact cross sections of the singlet excitations and the electron impact ionization have a similar energy dependence. Therefore, all of these processes, i.e., vibrational excitation via Lyman and Werner-band transitions, dissociation via ground state vibrational continuum and molecule ionization, are linearly proportional to the measured Lyman-band emission.[11] The described method has been originally developed for the diagnostics of hydrogen plasmas, but it can be applied to deuterium as well. However, the limited electron impact cross-sectional data, especially for the triplet states of deuterium, makes this somewhat challenging[6,16] as described hereafter.

Vibrationally resolved singlet excitation cross sections are virtually identical for hydrogen and deuterium.[16] However, electron impact ionization cross-sectional data are only available for the lowest vibrational level of the ground state. The ionization cross sections of hydrogen and deuterium molecules differ less than 15% at electron energies below 20 eV.[6]

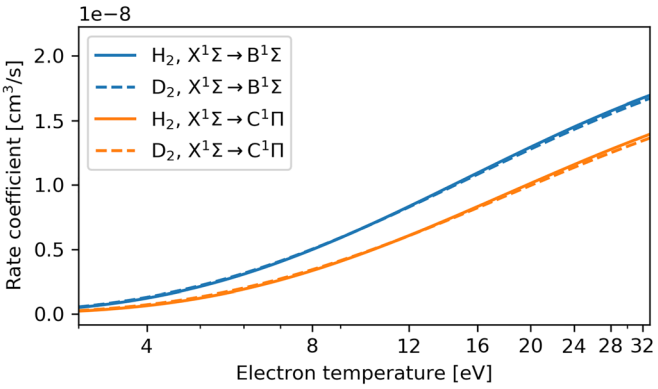

FIG. 2. Hydrogen and deuterium rate coefficients to $B^1\Sigma_u^+$ and $C^1\Pi_u$ states as a function of the Maxwellian electron temperature at $T_{vib} = 5000$ K (Boltzmann distribution). The cross sections are from Ref. 16.

The available cross-sectional data suggest that the ratio of the ionization and excitation rates of Lyman-band emitting states is very much the same for both hydrogen and deuterium. This means that the Lyman-band emission is proportional to the ionization rate in a similar manner for both hydrogen and deuterium. Although there is no difference between the excitation rates of hydrogen and deuterium to the $B^1\Sigma_u^+$ and $C^1\Pi_u$ states (Fig. 2), the decay of these states is approximately 20% more likely to populate high vibrational levels $\nu > 5$ of the ground state deuterium molecule owing to the differences in the Franck-Condon factors (see Fig. 3). In other words, the vibrational heating rates of the two isotopes through the electronic excitation of singlet states are different. The dissociation yields via $B^1\Sigma_u^+$ and $C^1\Pi_u$ continuum emissions have been found to be almost identical for hydrogen and deuterium in earlier spectroscopy studies.[17]

Optically forbidden electronic excitations to the triplet states are some of the main dissociation channels of hydrogen molecules. Virtually, all of these excitations decay to the lowest, repulsive, $b^3\Sigma_u^+$

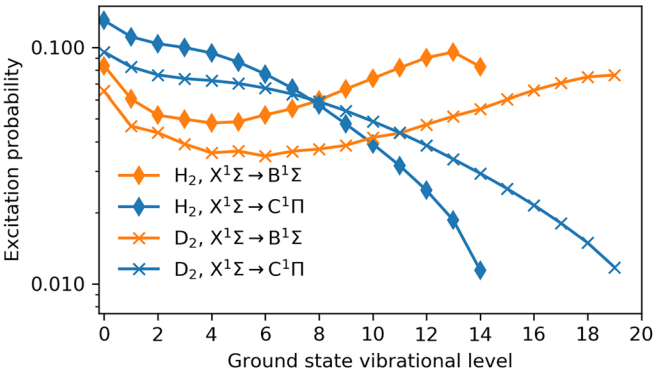

FIG. 3. Vibrational excitation distribution on the electronic ground state resulting from the hydrogen and deuterium molecule excitations to $B^1\Sigma_u^+$ and $C^1\Pi_u$ states at $T_{vib} = 5000$ K (Boltzmann distribution). The excitation probabilities are calculated using cross sections from Ref. 16 and Franck-Condon coefficients from Ref. 14.

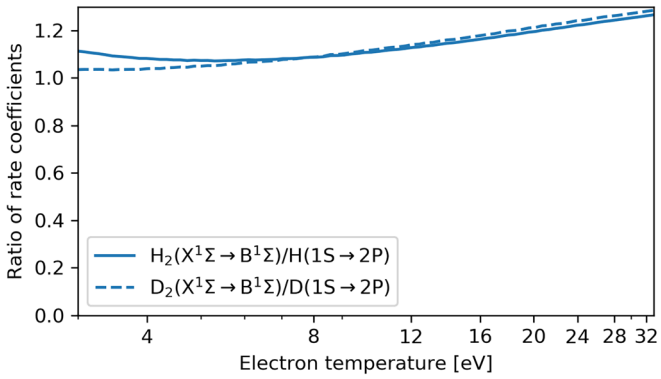

FIG. 4. Ratio of electron impact excitation rate coefficients to the lowest excited states of the atom ($1S \rightarrow 2P$) and molecule ($X^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+$) for hydrogen and deuterium as a function of Maxwellian electron temperature at $T_{vib} = 5000$ K (Boltzmann distribution). The cross sections are from Refs. 12 and 16.

triplet state. Some of the triplet excitations have also an intermediate step at the metastable $c^3\Pi_u$ state.[14] Virtually, all decay paths of this electronic state lead to molecule dissociation as well.[18] Both the molecule dissociation rate via triplet states and the production rate of the metastable $c^3\Pi_u$ molecules are linearly proportional to the measured molecular continuum emission.[11]

The available cross-sectional data for triplet excitations of deuterium limit the applicability of the method for the interpretation of the molecular continuum emission. The only available triplet excitation cross sections for deuterium are for the lowest, repulsive $b^3\Sigma_u^+$ state. This cross section is up to two times larger for deuterium than hydrogen.[6,19] The lack of deuterium excitation cross-sectional data for the upper triples states (e.g., $a^3\Sigma_g^+$, $e^3\Sigma_u^+$, $h^3\Sigma_g^+$, etc.) decaying to $b^3\Sigma_u^+$ and $c^3\Pi_u$ states do not allow concluding whether or not the molecular continuum emission is similarly proportional to the rates of dissociation and production of the metastable states for hydrogen and deuterium.

It has been discussed in the literature that the differences in dissociation rates between hydrogen and deuterium could potentially lead to the observed differences in the hydrogen and deuterium plasmas and the H^- and D^- ion beam performance. The ratio of the atomic Lyman-alpha emission to the molecular Lyman-band emission can be used as an indicator for changes in the dissociation degree between hydrogen and deuterium plasmas. This is because the electron impact excitation cross section for the lowest electronic transitions of hydrogen atoms ($1S \rightarrow 2P$) and molecules ($X^1\Sigma_g^+ \rightarrow B^1\Sigma_u^+$) is similar as a function of electron energy and insensitive to isotope effects.[16] Consequently, the ratio of these excitation rate coefficients has only a weak electron temperature dependence, and it is virtually the same for both isotopes as demonstrated in Fig. 4.

III. EXPERIMENTAL SETUP

The experimental setup used in this work is presented in Fig. 5. It consists of the LIISA (Light Ion—Ion Source Apparatus) ion source, a beam extraction system, a Faraday cup and a VUV-spectrometer.

The LIISA ion source is used as an H^-/D^- injector for the JYFL K-130 cyclotron. The LIISA is a DC (tantalum) filament-driven

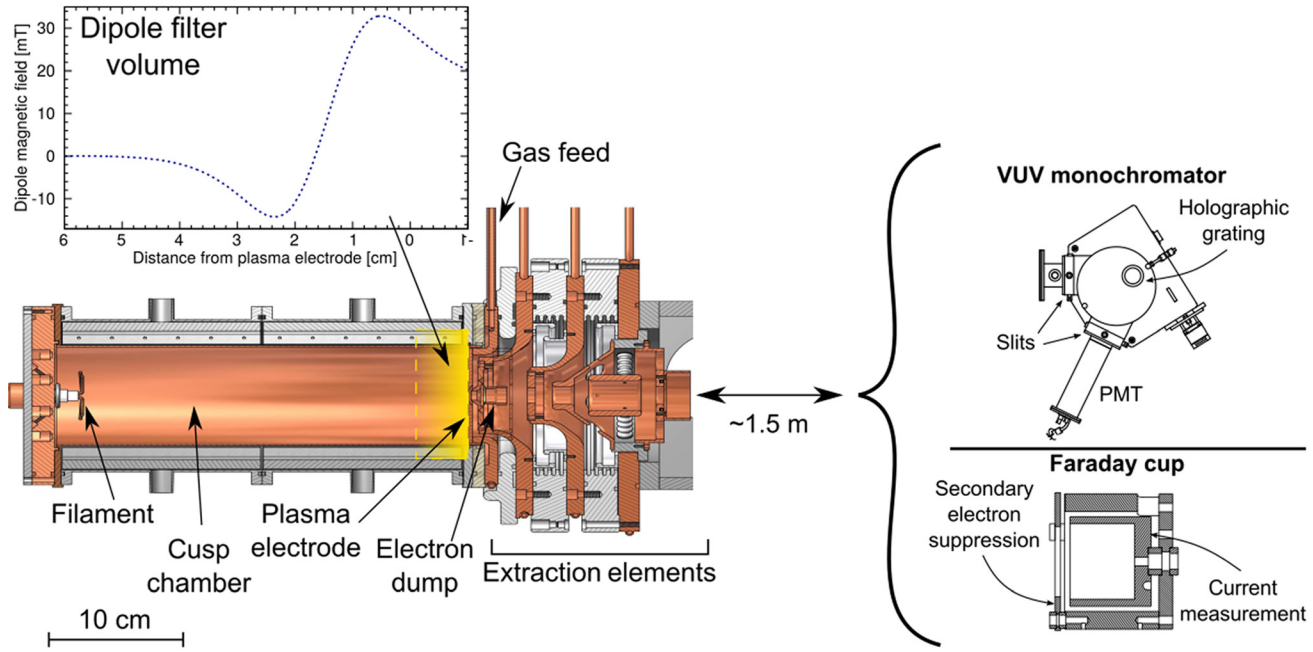

FIG. 5. The experimental setup. The negative and positive bias voltages of the filament and the plasma electrode, both referenced to the plasma chamber, i.e., ion source potential, are generated by 70 V/12 A and 20 V/10 A power supplies, respectively. The nominal extraction element voltages are as follows (from left to right): source potential, −5.9 kV; extraction (puller) electrode housing the electron dump, 1 kV; and first electrostatic Einzel lens, 1.5 kV, referenced to the (negative) ion source potential; and intermediate accelerating electrode, 2 kV; second Einzel lens, 2.3 kV; and third Einzel lens, 10.5 kV, referenced to the laboratory ground.

multicusp volume production ion source, designed to provide up to 3 mA of H^- at 5.9 keV final beam energy. It is essentially similar to the TRIUMF-type H^- ion sources,[7] the primary difference being a longer (300 mm) plasma chamber. In particular, the strength of the magnetic filter is equal in these two ion sources. At JYFL, a typical beam current requirement is approximately 1 mA, which is achieved with 70 V/10 A discharge voltage/current. Maximum levels for the arc discharge power and arc voltage are approximately 1 kW and 70 V (limited by the power supplies). The strength of the 10-pole cusp field is in the range of 300–350 mT on the wall of the plasma chamber, and the maximum strength of the transverse filter field is 30–35 mT on the source axis (Fig. 5).

The filament-driven arc discharge ion source is an appropriate choice for the presented study because it is a widely used ion source type and the results are well reproducible. The plasma is sustained by electrons emitted from the hot filament cathode and accelerated across the adjacent plasma sheath to the energy corresponding to the potential difference of the biased filament and the bulk plasma. The energy of these "hot" electrons is dissipated mainly in inelastic collisions with neutral particles (molecules and atoms) in discrete (7–15 V) steps, leading to ionization, electronic excitation, and molecular dissociation.[11,20] The resulting electron energy distribution (EED) consists of a cold electron population of "secondary" electrons (ionization and wall emission) superimposed with a flat, uniform, tail of the "primary" electrons emitted from the filament.[21] The temperature of the main electron population is so low (<3 eV, see e.g., Refs. 21 and 22) that virtually all excitations emitting VUV-photons are caused by the high energy tail of the EED. Due to the large discharge volume and the multicusp magnetic field increasing rapidly toward the chamber wall,[23] the high energy electrons are well confined and dissipate their energy very efficiently, thus producing a uniform plasma emission volume in the driver region. The effect of the uniform tail of the electron energy distribution function (EEDF) on the ionization and excitation rate coefficients is discussed thoroughly in Ref. 11.

The plasma dynamics in the extraction region differ from the driver region. The properties of the extraction region plasma depend strongly on the strength and topology of the transverse magnetic filter field and the potential of the biased plasma electrode. The magnetic filter suppresses the high energy tail of the EED penetrating to the extraction region, which results in weakly emitting plasma. The biased plasma electrode attracting electrons covers the entire extraction sidewall of the plasma chamber and affects the entire plasma dynamics of the extraction region strongly. It has been found that the optimum voltage of the biased plasma electrode in terms of efficient negative ion production and controlling the electron to ion ratio of the extracted beam is close to the plasma potential observed in the driver region.[5] However, it is emphasized that the driver region and the extraction region are well separated from the VUV-emission point-of-view, i.e., it was experimentally confirmed that the value of the plasma electrode bias voltage has no effect on the observed VUV-spectra.

The experiments were started by measuring the parametric dependence of the extracted H^- current using a Faraday cup made of copper and located 1.5 m downstream from the ion source. The aperture of the Faraday cup is 24 mm in diameter, and the secondary electrons were suppressed by applying a −50 V bias onto a ring electrode in front of the cup. It was confirmed that the beam spot was smaller than the Faraday cup aperture with adequate margin, by optimizing the extraction system and beam transport.

The ion source parameters were chosen to cover a certain range around the optimum source settings. The coextracted electron current was observed to be very sensitive to the biased plasma electrode voltage. Therefore, the coextracted electron to ion ratio was varied at each source operation point (pressure and power) by tuning the plasma electrode voltage and subsequently optimizing the extraction system (puller and first einzel lens voltages). The nominal potentials of the extraction electrodes are listed in the caption of Fig. 5.

The plasma electrode current at 11 V bias voltage was used for monitoring the plasma conditions in the extraction region. With 11 V bias voltage, the plasma electrode current, Faraday cup currents of H^-/D^-, and the current of the coextracted electrons were all saturated. All coextracted electrons are not collected by the electron dump, i.e., some of them are deflected back to the plasma electrode by the transverse magnetic field of the electron dump.[24] However, this does not affect the conclusions since the variations of the electron to ion ratio between the data points are significant.

After the ion beam measurements, the VUV-spectrometer was connected to the beam line and the VUV-spectra were scanned at identical operation parameters with the exception of the systematic variation of the plasma electrode bias, which affects the electron to ion ratio but not the VUV-emission intensity, and was therefore not performed during the VUV measurement. It has been found previously that the reproducibility of the ion source performance at certain parameter settings is excellent, i.e., the possible variations are on the order of a few percent. The spectrometer (range 120–650 nm) consists of a monochromator (McPherson Model 234/302), a holographic grating (600 grooves/mm), and a photomultiplier tube (ET Enterprises 9406B). The device was probing the plasma along an axial line of sight through the extraction aperture from a distance of about 1.5 m. The spectrometer was connected to the beam line, where the pressure was approximately 1×10^{-6} mbar during the measurements. The beam line Faraday cup was used as a shutter between scans to mitigate the effect of VUV-radiation induced defects of the spectrometer. The spectral response of the spectrometer was observed to remain practically constant through the measurement campaign. However, it is possible that the slight difference in hydrogen and deuterium spectra (Fig. 6) originates from the change of the spectral response. This is because deuterium spectra were recorded after hydrogen, and the response change is typically emphasized at short wavelengths, where the differences are observed.

The gas pressure was monitored with a penning gauge outside the plasma chamber where it varied between 1×10^{-5} mbar and 1×10^{-4} mbar. The Penning gauge reading was cross-calibrated with a Pirani gauge to correspond to a certain plasma chamber pressure. The same Pirani-gauge gas calibration coefficient (reading vs actual pressure) was used for both hydrogen and deuterium.

IV. RESULTS

The goal of this study has been to quantify possible differences in the ion source performance and VUV-emission between hydrogen and deuterium plasmas. As described in Sec. II, the VUV-emission is a probe for electron impact processes in the driver region. These electron impact processes produce precursors for the H^-/D^- ion production in the magnetic filter field, which is probed by measuring the IV-characteristics of the biased plasma electrode and the extracted currents of negative ions and coextracted electrons. These observables

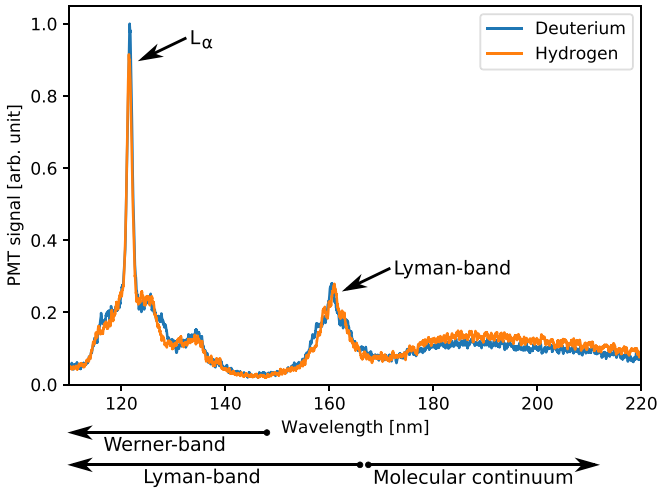

FIG. 6. The measured VUV spectra from hydrogen and deuterium plasmas. The spectra are measured at 0.5 Pa and 840 W arc discharge power (12 A, 70 V). The spectra are not corrected for spectral transmittance.

were measured as a function of the neutral gas pressure and arc discharge power around the optimum settings for the extracted H^--ion beam.

The neutral gas pressure in the discharge chamber was varied from 0.1 Pa to 1 Pa at 70 V arc voltage and 12 A arc current (840 W), which is often found to be the practical range for negative ion production in H^-/D^- ion sources. The arc discharge power was adjusted by varying both the arc voltage and the arc current in separate parametric sweeps at 0.4 Pa pressure, which is the optimum for the negative ion production from both isotopes. The results are displayed in Figs. 7 and 8, showing the normalized VUV emission in different wavelength ranges, and Figs. 9 and 10, showing the negative ion currents.

Significant differences between the VUV-spectra of hydrogen and deuterium were not found (see Fig. 6). The response of the VUV-spectrum to the variations of the neutral gas pressure and arc discharge power was similar for both gases as shown in Figs. 7 and 8. The emission rates of the spin-allowed electronic transitions (Lyman-alpha, Lyman-band, and Werner-band) are linearly proportional to the total arc discharge power without any preference toward the applied arc current or voltage (Fig. 7). Meanwhile, the emission from the spin forbidden excitations (molecular continuum) was observed to depend linearly on the discharge current, which is proportional to the number of electrons emitted from the hot filament. This is demonstrated in Fig. 7 where the molecular continuum data points at constant discharge currents are connected with solid lines. These dependencies can be explained by the discrete nature of the inelastic excitations dissipating the energy of the electrons emitted from the filament. The cross sections of the Lyman- and Werner-band excitations increase monotonically up to 40 eV and then decrease slowly with increasing energy, whereas the cross section for triplet state excitations emitting in molecular continuum has a sharp peak below 20 eV (see Fig. 1). This means that hot electron dissipating energy in consecutive inelastic collisions can cause multiple excitations to singlet states but only one excitation to triplet states. Thus, the molecular continuum signal is directly proportional to the number of hot electrons, i.e., the discharge current. The dependence of the VUV-emission intensity on the neutral gas

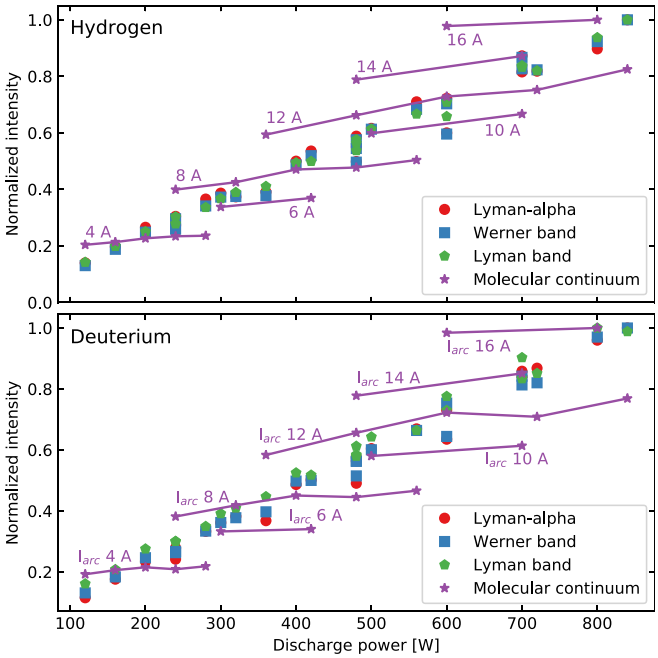

FIG. 7. The VUV emission as a function of the arc discharge power in different emission bands at 0.4 Pa neutral gas pressure. The data are normalized to the maximum intensity observed during the parameter sweep.

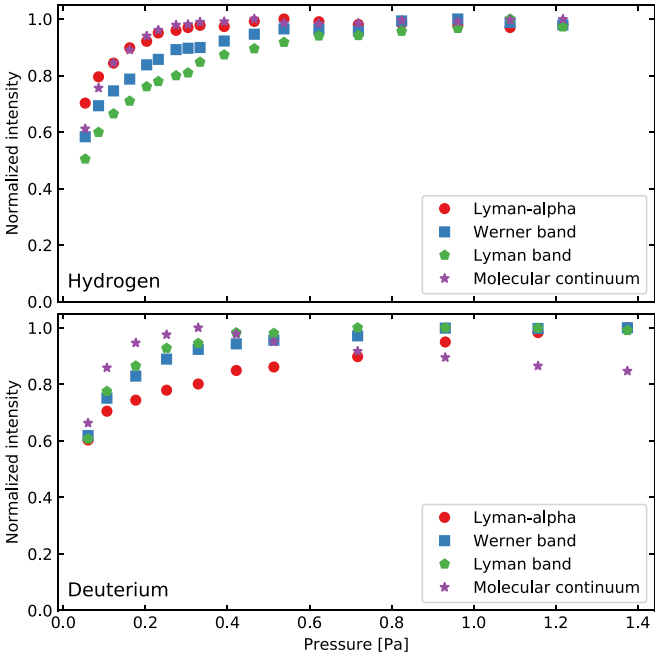

FIG. 8. The VUV emission as a function of neutral gas pressure in different emission bands at 70 V arc voltage and 12 A arc current (840 W). The data are normalized to the maximum intensity observed during the parameter sweep.

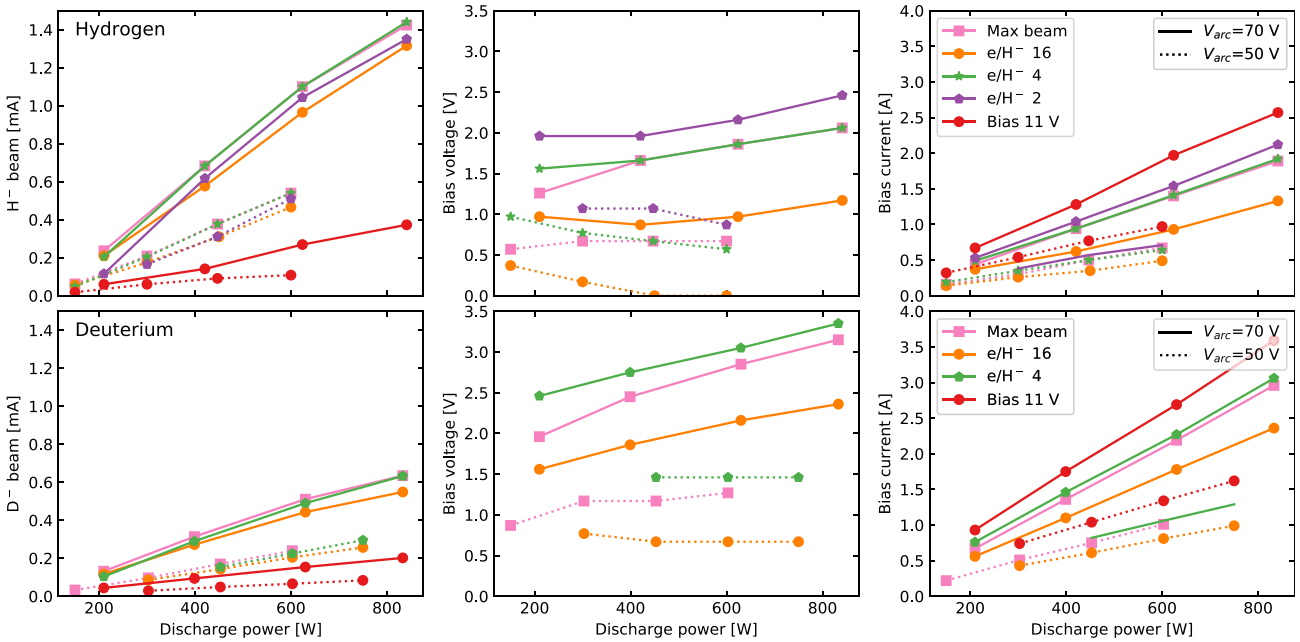

FIG. 9. Measured H^- currents and biased plasma electrode parameters as a function of discharge power for different H^-/e-ratios. The measurements were performed using two different arc voltages (50 V and 70 V) at 0.4 Pa neutral gas pressure.

pressure is similar for all the emission bands and both isotopes with the exception of the molecular band emission of deuterium, decreasing slightly at pressures above the optimum. For the other emission bands, the intensity increases up to 0.4 Pa and then saturates at that level.

The absolute VUV-emission power was previously measured for hydrogen plasma from the same ion source and reported in Ref. 10. The data were used for estimating the volumetric rates of ionization, dissociation, and production of high vibrational levels in the

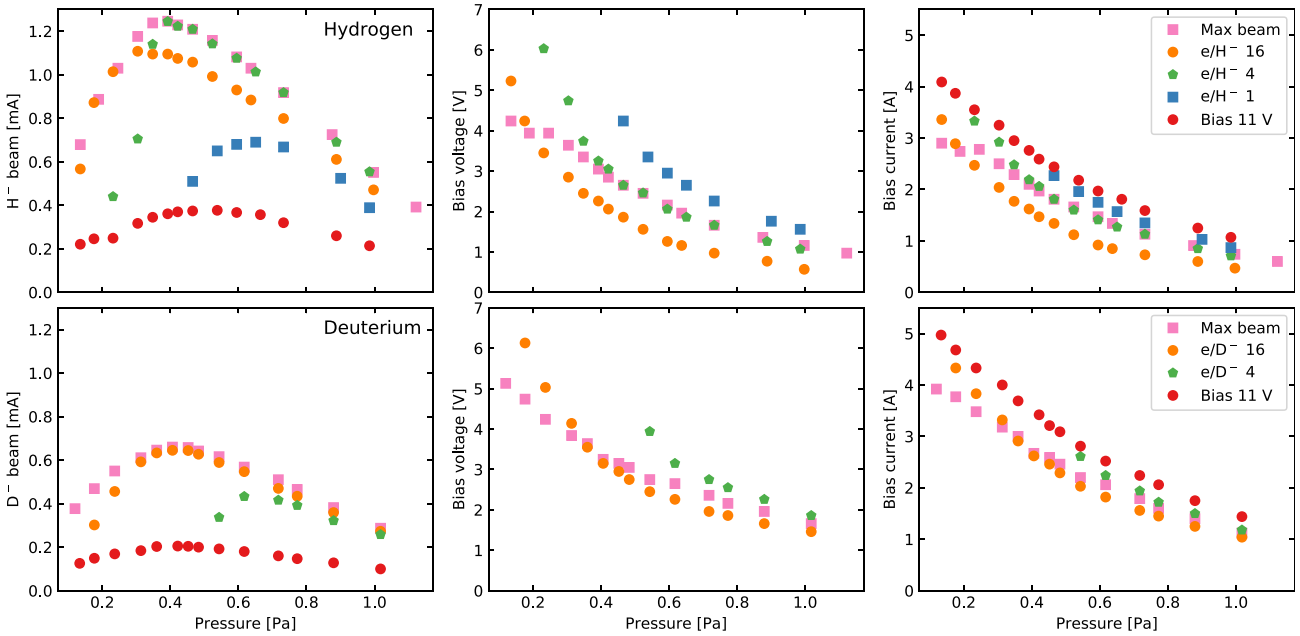

FIG. 10. Measured H^- currents and biased plasma electrode parameters as a function of neutral gas pressure for different H^-/e-ratios at 70 V arc voltage and 12 A arc current (840 W).

TABLE I. Comparison of the volumetric rates (in units of $\times 10^{16}$ 1/cm^{3}s) of different plasma processes between hydrogen and deuterium in the line-of-sight volume visible to the VUV-diagnostics. The data for hydrogen are taken from Ref. 11.

Reaction	Hydrogen	Deuterium
Ionization (H_2^+)	7–15	7–15
Electronic excitation to $B^1\Sigma_u^+, C^1\Pi_u$	12–14	12–14
Vibrational excitation of $X^1\Sigma_g^+ (\nu \geq 5)$ via $B^1\Sigma_u^+, C^1\Pi_u$	7.0–7.8	8.4–9.4
Dissociation via $B^1\Sigma_u^+, C^1\Pi_u$	1.8–2.0	1.8–2.0
Dissociation via $b^3\Sigma_u^+$	2.5–5.8	2.5–5.8[a]
Excitation to metastable $c^3\Pi_u$ (max.)	0.7–1.5	0.7–1.5[a]

[a]Assumes that all the excitation cross sections to triplet states of hydrogen and deuterium scale similarly to the cross sections of direct excitation to the $b^3\Sigma_u^+$-state.

line-of-sight of the VUV-diagnostics apparatus.[11] The previously published results from Refs. 10 and 11 and the present data comparing the differences of hydrogen and deuterium can be applied to estimate the corresponding rates for deuterium plasmas. The comparison is presented in Table I. The volumetric rates for the hydrogen plasma are from Ref. 11, whereas the values for the deuterium plasma (where possible) are based on those measured with hydrogen and the theoretical treatment presented in Sec. II.

The ion source performance was studied by optimizing the extraction system for different coextracted electron to negative ion current ratios ranging from 1 to 16. The values of the extracted H^-/D^- currents and the biased plasma electrode voltages and currents were recorded at each setting. The results are presented in Fig. 9 as a function of the arc power and in Fig. 10 as a function of the neutral gas pressure.

The extracted D^- current is systematically lower than the H^- current by approximately 50% at the same operation parameters. At the same time, the minimum ratio of the coextracted electrons to negative ions is higher by a factor of four for deuterium. Furthermore, it was observed that the biased plasma electrode voltage and corresponding current, required to achieve a certain ratio of coextracted electrons to negative ions (when possible), are 20% higher for deuterium. The voltage of the plasma electrode was observed to be proportional to the arc voltage at a constant coextracted electron to negative ion ratio and depend only weakly on the total arc power.

The optimum neutral gas pressure (approximately 0.4 Pa) for negative ion production is practically identical for both hydrogen and deuterium. It is worth noting that the light emission saturates at this pressure. The reduced light emission at lower pressures implies that the energy dissipation of the hot electrons emitted from the biased filament is limited by insufficient magnetic confinement and their energy is not completely dissipated in inelastic collisions (ionization and electronic excitations). This implies that at suboptimal pressure, the negative ion production could be limited by either the insufficient production of high vibrational levels of the ground state molecules or the lack of cold electrons (in the filter field region) produced in molecular ionization. The latter is derived from the fact that the ionization rate, i.e., the production rate of cold electrons, is proportional to the excitation rate to a singlet state. This standpoint is supported by the data in Ref. 25, showing with the Lyman-band emission used as an indicator that in a microwave discharge at low pressures, the negative ion density in the filter field region is not limited by the production rate of high vibrational levels. At pressures higher than the optimum, it could be argued that the collisional destruction rate of the negative ions becomes too high and affects their survival probability. It is also possible that the density of vibrationally excited molecules decreases at high pressure due to the collisional vibrational energy transfer of the high vibrational levels.[26] Finally, the difference between hydrogen and deuterium can be most likely attributed to their different diffusion properties.

V. DISCUSSION

The results presented in this paper indicate that the maximum extracted deuterium beam current is consistently about half of the extracted hydrogen beam current, while the minimum ratio of the coextracted electrons to negative ions is approximately four times larger for deuterium than hydrogen. These results are similar to those reported, e.g., in Refs. 9 and 27. Likewise, it has been found with the large area negative ion sources for neutral beam injection that the coextracted electron ratio is notably higher for deuterium.[28] However, the VUV-emission intensities and spectra were found to be similar for hydrogen and deuterium discharges, i.e., there is no correlation between the beam currents and the VUV-emission intensity.

The VUV-emission and the extracted currents of the negative ions and electrons probe different plasma regions. The VUV-emission yields information on the electron impact processes in the driver region, whereas the extracted beam current reflects the DEA rate and plasma diffusion through the magnetic filter field. The electron impact processes in the driver region produce electrons through ionization and high vibrational levels of hydrogen/deuterium molecules through electronic excitations, which are the key ingredients for the negative ion production via DEA. On the other hand, the extracted beam currents are determined as a result of complex plasma chemistry and diffusion processes, which depend on the electron temperature and vibrational temperature of the molecules and plasma properties such as electronegativity (formation of ion–ion plasmas[29]).

The VUV-spectra of hydrogen and deuterium being almost identical imply that there are no significant differences in the volumetric rates of ionization or production of high vibrational levels. In previous studies (see, e.g., Refs. 28 and 30), it has been discussed that the apparent performance difference could be due to differences in the dissociation rate and degree. However, the constant ratio of the Lyman-alpha to Lyman-band emission implies that there is no significant difference in the dissociation degrees between the two plasmas in the studied filament ion source. This is also supported by the observation that the molecular continuum emission is similar for hydrogen and deuterium, which assuming similar cross section scaling for the excitation of all triplet states[31] would imply that the dissociation rate is similar for both plasmas.

All the observations suggest that the plasma diffusion in the filter field explains the difference between hydrogen and deuterium beam currents. Although the production rates of the precursors of the H^-/D^- DEA process, namely, cold electrons through ionization and ground state molecules at high vibrational levels through electronic excitation and subsequent decay, are virtually the same, the complex diffusion dynamics in the magnetic filter field depend strongly on the isotope. The cross sections of DEA from low vibrational levels ($\nu < 6$)

of hydrogen and deuterium differ by orders of magnitude.[16] At the same time, plasma diffusion through the filter field is a combination of diffusive transport across and along the magnetic field with its nontrivial balance being reviewed in Ref. 32. Both of these diffusion mechanisms are proportional to the ion (thermal) speed, which scales as $1/\sqrt{m_i}$. This means that the diffusion of deuterium ions in the filter field is slower, which can be expected to lead to a sharper plasma density gradient across the field and higher plasma potential in comparison to hydrogen.

In a recent study,[27] with a similar filament-drive ion source, it was found that optimizing the extracted current of D^- requires a stronger filter field than optimizing the current of H^-. A Langmuir-probe was then used to confirm that the stronger field is required to reduce the electron temperature near the plasma electrode to ~0.5 eV, favorable for the DEA process and survival of the negative ions.[27] The higher electron temperature observed in Ref. 27 across the filter field volume at certain magnetic field strength implies that the plasma potential is indeed higher in deuterium discharge. The higher plasma potential for deuterium plasmas is commonly observed[22,28] and also indirectly supported by the higher biased plasma electrode voltage for deuterium (see Figs. 9 and 10) found here. The cross field diffusion can lead to the formation of an ion-ion plasma,[29] which is also observed in negative ion sources[33,34] and implied by the very low coextracted electron current with hydrogen observed in this study. The higher coextracted electron current with the deuterium implies lower negative ion density in the extraction region, whereas it has been observed with a Langmuir-probe[27] that the electron density at the plasma electrode could be even higher for deuterium at comparable field strength. These results are consistent with the data presented here, and altogether, they emphasize the role of diffusion in determining the extracted negative ion current and electron-ion ratio over the production of molecules at high vibrational levels.

It is worth noting that there might be significant differences in the rates of electron impact processes and dissociation degrees of hydrogen and deuterium between the studied filament ion source and other discharges utilizing different plasma chamber materials and plasma heating methods (see, e.g., Refs. 8 and 30). It has been demonstrated that the surface materials[35,36] and the plasma heating method[20,37] have significant effects on the dissociation degree and relative rates of the electron impact processes. The technological solutions of the filament ion source are efficient for the volume production of H^-/D^- ions. The uniform high energy tail of the EEDF favors the ionization and production of high vibrational levels through electronic singlet excitation,[11,20] whereas the dissociation rate and degree are reduced by the EEDF being unfavorable for electronic triplet excitations and the metallic plasma chamber surface being beneficial for atom association to molecules.[20]

The ratio of the coextracted electron to negative ion current is commonly used as a single number to compare the performance of different types of ion sources. The careful study presented here implies that this ratio is very sensitive to the operational parameters of the ion source, especially the neutral gas pressure. Because the choice of operational parameters, such as the neutral gas pressure, is often a compromise between the actual H^-/D^- production in the plasma volume and technological limitations (e.g., ion beam extraction and focusing system), it is worth noting that a simple comparison of the coextracted electron to negative ion ratio might not always yield information on the actual potential of the ion source but could instead reflect the limitations of the applied technological solutions including the ion source and extraction system.

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