

Laser induced fluorescence of singly ionized atomic iodine: Measurements in the plasma source of an electric propulsion device

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A laser induced fluorescence (LIF) scheme is investigated to probe singly ionized iodine ions (I^+) in electric propulsion devices. The transition $6s\ ^5S_2^o \rightarrow 6p\ ^5P_3$ at 516.261 nm is considered and the theoretical computation of the weights and positions of the hyperfine structure is carried out. First, the measurement of the fluorescence signal is performed in the ionization chamber of an rf gridded ion engine, the PEGASES thruster, demonstrating that the chosen LIF scheme is well suited for the study of electric propulsion devices operating with iodine. Second, spatial measurements of the temperature, velocity, and density are taken in this plasma source for several conditions of iodine pressure from 0.5 to 10 mTorr. First, an increase of the temperature of the ionic excited population close to the antenna is observed. Second, the analysis of the Doppler shift of the LIF profile shows the acceleration of the ions in the source. Third, the comparison of the measured LIF profiles with previous measurements shows that the density of the probed lower excited state is proportional to that of the ground state in the conditions of the experiment.

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I. INTRODUCTION

In the context of an increasing number of spacecrafts using electric propulsion launched into space, the production of xenon, which is the most commonly used propellant, might reach a bottleneck in the coming years. To address this challenge, industrials are exploring potential alternatives that include other noble gases such as krypton and argon, as well as molecular components [1–3]. In particular, molecular iodine (I_2) provides propulsion capabilities similar to that of xenon because it shares some of its interesting properties: a heavy mass and a low energy of ionization [4,5]. In addition, iodine offers a major operational advantage: it is solid at standard temperature and pressure conditions. This characteristic enables high-density storage and eliminates the need for pressurized gas tanks on spacecrafts, making it a highly attractive candidate for future propulsion technologies [6]. However, the use of a novel propellant must come with the development of diagnostic techniques to be able to probe the different species constituting the plasma produced by these electric propulsion devices, for device development and optimization as well as on-ground testing. Unlike noble gas plasmas, iodine plasmas present a much more complicated chemistry involving a larger combination of neutral and charged species including electrons, molecules, atoms, and ions (mainly I^+ , I_2^+ , and I^-). This complexity multiplies the efforts required to be able to probe these species. Moreover, another issue for on-ground testing of iodine-fueled thrusters is the corrosive nature of this propellant. Hence, nonintrusive

optical diagnostics are particularly suited for the study of iodine plasmas and should be favored over *in situ* electrostatic diagnostics. This paper focuses on the use of the laser induced fluorescence (LIF) diagnostic to probe the singly ionized atomic iodine (I^+) in a plasma. The energy level diagram of this ion, in the range of interest for this paper, is represented in Fig. 1. Given the limited available spectroscopic

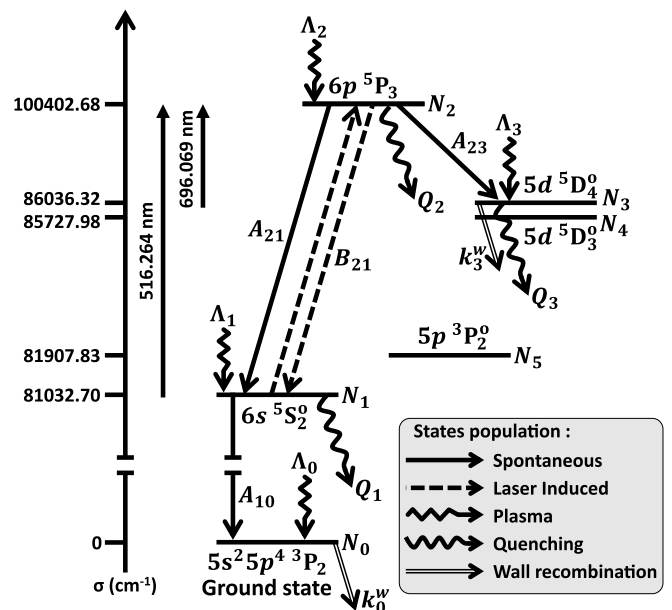


FIG. 1. Energy levels diagram with the main population and depopulation mechanisms.

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data at the time, Hargus *et al.* have identified several transitions relevant to perform this diagnostic and identified the transition $5s^25p^3(^4S^o)5d\ ^5D_4^o \rightarrow 5s^25p^3(^4S^o)6p\ ^5P_3$ at 696.069 nm as the best candidate because of the metastability of the lower state [7], even though its lifetime is limited by the wall recombination. The authors also found the transition $5s^25p^3(^4S^o)6s\ ^5S_2^o \leftarrow 5s^25p^3(^4S^o)6p\ ^5P_3$ at 516.261 nm to be the best transition for the collection of the fluorescence. Following this effort, Steinberger and Scime [8], and more recently Lazo *et al.* [9] investigated this LIF scheme and performed experiments in a plasma generated in a microwave Evenson cavity in order to work in a controlled environment reproducing plasma conditions similar to that of an electric propulsion device. The authors measured a fluorescence signal in this cell and paved the way for the effort aimed at probing singly ionized atomic iodine in electric propulsion plasmas. However, their investigation revealed that the hyperfine structure of the transition (i) could not be established with a sufficient resolution with the spectral data available at the time of this study [10] and (ii) is not split enough or negligible to allow the estimation of the ion temperature from the LIF measurements with a satisfactory precision. The recent tabulation of spectroscopic data by Ashok *et al.* constitutes a further motivation for the present work [11].

In order to overcome the limitations mentioned above, we propose in this paper to investigate the LIF resulting from the excitation of the transition $6s\ ^5S_2^o \rightarrow 6p\ ^5P_3$ at 516.261 nm, the resonant fluorescence light being collected at the same wavelength. In the plasma condition of the experiment presented below, the electron density is $n_e \approx 10^{18}\text{ m}^{-3}$ and the density of singly ionized iodine is of the same order of magnitude [12,13]. A tiny fraction of the I^+ population is in the probed excited state, as shown by emission spectroscopy measurements [14]. Unlike the lower $5d\ ^5D_4^o$ state that was identified in the previously cited references, the lower state of the transition selected in the present work is not metastable. In fact, the $6s\ ^5S_2^o$ state is mixed with around 8% distributed among the $6s'\ ^3D_2^o$, the $6s'\ ^1D_2^o$, and the $6s''\ ^3P_2^o$ states (see Table 6 of Ref. [10]), which implies a leakage path to the ground state of I^+ . This effect reduces considerably the population density of the lower level, but is not prohibitive since LIF spectroscopy is a very sensitive diagnostic that allows one to measure absolute densities as small as 100 atoms/cm^3 [15]. Moreover, as shown in this paper, the hyperfine structure of the considered transition is sufficiently split and resolved to allow the ion temperature to be estimated with a very satisfactory degree of accuracy. Note that in this visible spectral range, there are numerous molecular iodine lines [16]. It is however verified below that the molecules are nearly fully dissociated and that the spectral selectivity of the detection eliminates any stray molecular resonance on the ionic signal. Results present the measurement of a fluorescence signal in an iodine-fueled electric propulsion device, showing the suitability of this LIF scheme for electric propulsion applications. Note that the temperature measured in this paper is that of the nonmetastable lower level, which is not necessarily the temperature of the ground state. In addition, spatial measurements of the ion velocity in the chamber for several conditions of pressure show the suitability of this diagnostic for measuring velocities.

II. LASER INDUCED FLUORESCENCE

A. Intensity of the LIF signal

The system considered in this paper is represented in Fig. 1. The subscripts 0, 1, 2, 3, 4, and 5 refer respectively to the $5s^25p^4\ ^3P_2$ (ground state), the $6s\ ^5S_2^o$ (lower), the $6p\ ^5P_3$ (upper), the $5d\ ^5D_4^o$, the $5d\ ^5D_3^o$, and the $5p\ ^3P_2^o$ levels. As indicated in Fig. 1, the population of a level i by plasma excitation is described by the parameter Λ_i . The depopulation by collision is described by the quenching parameter Q_i and the depopulation by recombination at the wall is described by the parameter k_i^w . Two mechanisms contribute to the fluorescence from the upper to the lower level (transition $2 \rightarrow 1$). On the one hand, the fluorescence of the plasma comes from the ions naturally present in the upper state. As indicated in Fig. 1, the spontaneous emission from a level j to a level i is described by the Einstein coefficient A_{ji} . The lifetime of the upper state, noted τ_2 , is defined through the relation

$$\frac{1}{\tau_2} := A_2 = \sum_{k \neq 2} A_{2k} \quad (1)$$

where [17] $\tau_2 = 12.6 \pm 0.6\text{ ns}$ ($A_2 = 79.4 \times 10^6\text{ s}^{-1}$) and is distributed among the levels 1, 3, 4, and 5 [18]. On the other hand, the laser-induced fluorescence comes from the ions present in the upper state after their excitation by the laser. The excitation and deexcitation processes induced by laser between two levels are described by the Einstein coefficients B_{ij} and B_{ji} respectively. Using the rate equation formulation in the stationary regime, in the presence of a laser of intensity $\mathcal{I}$ that excites the transition $1 \rightarrow 2$, the system can be reduced to an open two-level system and the density of the upper state population, noted N_2 , can be expressed under the following general form [19,20]:

$$N_2(\mathcal{I}) = N_2^0 + \frac{\mathcal{I}}{\mathcal{I} + \mathcal{I}_s} \times \frac{A_{10}}{A_2 - A_{21} + \frac{g_1}{g_2} A_{10}} \Delta N^0, \quad (2)$$

$$\mathcal{I}_s = \frac{A_{10}A_2}{B_{12} \frac{g(\omega)}{c} \left(A_2 - A_{21} + \frac{g_1}{g_2} A_{10} \right)}, \quad (3)$$

$$\Delta N^0 = N_1^0 - \frac{g_1}{g_2} N_2^0 = \frac{\Lambda_1 A_2 + \Lambda_2 \left(A_{21} - \frac{g_1}{g_2} A_{10} \right)}{A_{10}A_2} \quad (4)$$

where c is the speed of light, $g(\omega)$ is the normalized line-shape profile of the transition, g_i is the degeneracy of the level i , N_1^0 and N_2^0 are respectively the densities of the lower and upper states without laser excitation, and $\mathcal{I}_s$ is called saturation intensity. In the formulation 2, the quenching rates are neglected because of the low pressure operation [21] ($\approx 1\text{ Pa}$). Equation (2) highlights the fact that the fluorescence signal, noted S^{fluo} , can be decomposed into the sum of the plasma fluorescence S^0 and laser-induced fluorescence S^{LIF} , such that

$$S^{\text{fluo}} = S^0 + S^{\text{LIF}} = \eta A_{21} (N_2^0 + N_2^{\text{LIF}}) \quad (5)$$

where η is the instrumental factor that is the product of the quantum efficiency of the detector, the gain of the photomultiplier, the transmission of the optical setup and the solid angle of light collection, and a coefficient that takes into account the anisotropy of the fluorescence [22]. As detailed in the experimental apparatus description, the synchronous detection and collection of the fluorescence in an optical fiber

TABLE I. Magnetic dipole and electric quadrupole coupling coefficients used in this work, taken from Ref. [24].

Level	A (10^{-3} cm^{-1})	B (10^{-3} cm^{-1})
$6s \ ^5S_2$ (lower)	92.41	4.6
$6p \ ^5P_3$ (upper)	4.54	-11.0

partially eliminates the light emitted by the plasma and the signal measured experimentally is reduced to S^{LIF} .

B. Hyperfine structure

As introduced above, the excitation path investigated in this work is the transition from the excited state $6s \ ^5S_2$ at 81032.70 cm^{-1} to the excited state $6p \ ^5P_3$ at $100402.68 \text{ cm}^{-1}$. The wave number of the center of this transition has been precisely measured in the literature [11] at $\sigma_0 = 19370.0336(4) \text{ cm}^{-1}$. Due to the nonzero nuclear spin of iodine $I = 5/2$, the upper and lower levels of the transition are split into hyperfine levels. For each hyperfine level, the total angular momentum F is computed from the sum of the spin angular momentum I and the total electronic angular momentum J , i.e. $\vec{F} = \vec{I} + \vec{J}$ such that

$$|J - I| \leq F \leq |J + I|. \quad (6)$$

The center of gravity of each hyperfine level is shifted from the fine structure by an energy increment ΔE calculated as follows [23]:

$$\Delta E = A \frac{C}{2} + B \frac{3C(C+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)} \quad (7)$$

where $C = F(F+1) - I(I+1) - J(J+1)$ and A and B are respectively the magnetic dipole and electric quadrupole coupling coefficients. The values of these coefficients are taken from Ref. [24] and are recalled in Table I. Note that the value of the coupling coefficients tabulated more recently in Ref. [11] does not allow one to find precisely the position of the hyperfine lines measured experimentally. The allowed transitions from one hyperfine level F of the lower state to one hyperfine level F' of the upper state must respect the rule $\Delta F = F' - F = \{0, \pm 1\}$. They are represented with red arrows in Fig. 2.

In the low-field excitation regime, with the optically thin approximation, the laser-induced fluorescence signal can be expressed from Eqs. (2), (3), and (5):

$$S^{\text{LIF}}_{\mathcal{I} < \mathcal{I}_s} = \eta B_{12} \frac{g(\omega)}{c} \frac{A_{21}}{A_2} \mathcal{I} \Delta N^0. \quad (8)$$

From Eq. (4), one can write the population difference between two hyperfine levels of an allowed transition $F \rightarrow F'$:

$$\Delta N_{F \rightarrow F'} = \frac{2F+1}{(2I+1)(2J+1)} \Delta N^0. \quad (9)$$

Similarly, noting that [25]

$$A_{21} = \frac{\hbar \omega_0^3}{\pi^2 c^3} B_{21}, \quad B_{12} = \frac{g_2}{g_1} B_{21}, \quad (10)$$

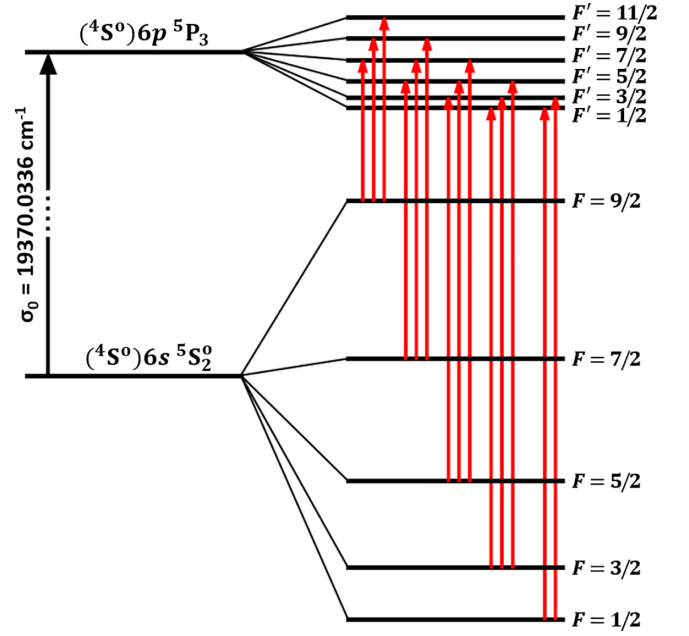


FIG. 2. Hyperfine structure of the $6s \ ^5S_2 \rightarrow 6p \ ^5P_3$ transition. The allowed transitions are represented with red arrows.

Eq. (8) can be expressed as a sum, on every allowed hyperfine transition, of the partial LIF signals $S^{\text{LIF}}_{F \rightarrow F'}$, expressed as

$$S^{\text{LIF}}_{F \rightarrow F'} = \eta \frac{g(\omega) \mathcal{I}}{c} \frac{A_{21}}{A_2} B_{F \rightarrow F'} \Delta N^0_{F \rightarrow F'} \quad (11)$$

$$= \eta g(\omega) \mathcal{I} \frac{A_{21}}{A_2} \frac{\pi^2 c^2}{\hbar \omega_0^3} A_{F' \rightarrow F} \frac{(2F'+1)}{(2I+1)(2J+1)} \Delta N^0 \quad (12)$$

where the partial Einstein coefficient $A_{F' \rightarrow F}$ reads [26]

$$A_{F' \rightarrow F} = (2F+1)(2J'+1) \left\{ \begin{matrix} F & 1 & F' \\ J & I & J \end{matrix} \right\}^2 A_{21} \quad (13)$$

and the notation $\{ \}$ stands for the 6- j Wigner symbol [27]. From Eqs. (12) and (13), it comes about that

$$S^{\text{LIF}} = \sum_{F \rightarrow F'} S^{\text{LIF}}_{F \rightarrow F'} = \eta \frac{\pi^2 c^2}{\hbar \omega_0^3} \frac{A_{21}}{A_2} \mathcal{I} g(\omega) \sum_{F \rightarrow F'} \xi_{F \rightarrow F'} \quad (14)$$

where the coefficient $\xi_{F \rightarrow F'}$, also called the weight of the hyperfine transition, reads

$$\xi_{F \rightarrow F'} = \frac{(2F+1)(2J'+1)(2F'+1)}{(2I+1)(2J+1)} \left\{ \begin{matrix} F & 1 & F' \\ J & I & J \end{matrix} \right\}^2. \quad (15)$$

The formulation (14) shows that the line-shape function $g(\omega)$ is obtained from a scan of the laser frequency across the transition. The observed spectral profile results from a combination of homogeneous broadening, described by a Lorentzian profile, and inhomogeneous (or Doppler) broadening, described by a Gaussian profile. Homogeneous broadening includes both the finite lifetime of the transition (natural broadening) and the collisional broadening arising from elastic or inelastic particle collisions. Doppler broadening occurs because each atomic velocity class experiences a different Doppler shift relative to the resonant frequency. Even though the pressure in our experiment is relatively low ($p = 1.17 \text{ Pa}$), collisional broadening remains difficult to quantify due to the lack of

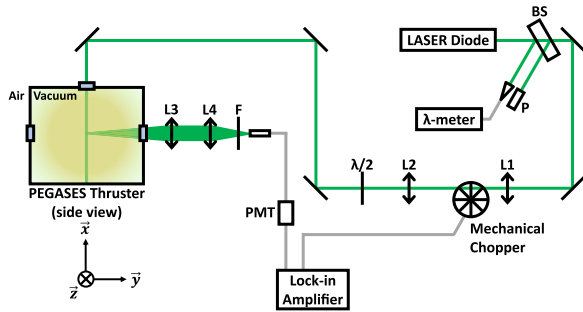


FIG. 3. Schematic of the side view of the experimental setup. Corresponding labels: BS for beam splitter, P for photodiode, $\lambda/2$ for halfwave plate, F for bandpass filter, and L for lenses.

available spectroscopic data. Nevertheless, by noting that $g(\omega)$ takes a Voigt profile when the Doppler and Lorentzian linewidth are of the same order, the value of the parameters $\Delta\nu_H$ and $\Delta\nu_D$ characterizing respectively the homogeneous and inhomogeneous broadening [28] can be estimated from a fit of the experimental profile.

III. EXPERIMENTAL APPARATUS

The plasma source used in this work is called the PEGASES thruster. It is an inductively coupled plasma source operating at a rf of 4 MHz which features a biased grid to accelerate ions and produce a thrust force. In this work, the grid is left unbiased to ensure a better confinement of the plasma inside the source and increase the density of the charged species. The available range of rf power is comprised between 50 and 400 W and this source works with various propellants, in particular with pure iodine at a mass flow rate comprised between 1 and 10 sccm. A detailed study of this plasma source working with iodine as well as the experimental setup can be found in several references [4,12]. Figure 3 represents a schematic of the side view of the LIF experimental setup. In the referential (x, y, z) indicated in this figure, the main axis of the thruster is the z axis, where $z = 0$ corresponds to the plane of the antenna. In a first place, measurements are performed in the plane $z = 21$ mm. Spatial measurements are discussed in Sec. V. The cw laser used in this experiment is a Toptica DL Pro green laser diode whose wavelength and intensity are monitored by an Ångström WS-U wavemeter (λ -meter) and the photodiode (P) respectively. The wavelength of the laser is driven by a sawtooth signal at the period $\tau_{\text{scan}} = 128$ s. The diameter of the collimated beam is first reduced to approximately 3 mm with the two lenses (L1) and (L2) and its polarization is set by a half-wave plate ($\lambda/2$) before being sent in the plasma inside the vacuum chamber. One major drawback of implementing such experimental setup is the limited optical access for the fluorescence collection due to the thruster walls. To overcome this limitation, a set of two collection lenses (L3) and (L4) is used to image the fluorescence in an optical fiber of diameter 400 μm . The diameter of the optical fiber acts as a spatial filter; in fact it defines the volume in which the light is collected. This volume is estimated to less than 1 mm^3 . Hence, this collection mechanism is particularly suited for spatially resolved measurements for electric

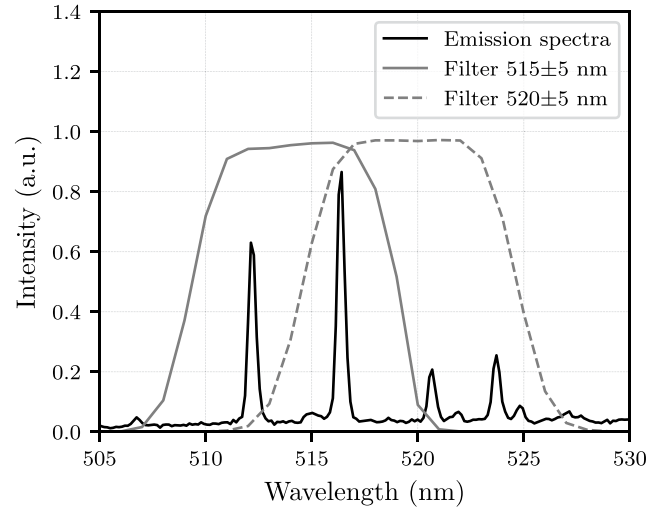


FIG. 4. Plasma emission spectra inside PEGASES and transmission of the two filters used in the experiment.

propulsion applications. The fluorescence light is collected by a Hamamatsu R3896 photomultiplier tube (PMT) biased at -260 V after passing through two bandpass optical filters (F), one centered around 515 ± 5 nm and the other centered around 520 ± 5 nm in order to prevent the stray light of the plasma from being collected. The spectral transmission of the two filters is represented in Fig. 4 along with an emission spectrum of the plasma. This figure shows that the superimposition of the two filters allows one to filter out the plasma light emitted by the molecules (around 512 and 521 nm) while not filtering the light in the region of interest around 516 nm. Note that the fluorescence can also be collected around 696 nm. In this case, only one filter is required. In this configuration, the signal is lower, in agreement with a lower relative line intensity observed at this wavelength in other experiments [10,29], but has the same profile. This confirms that collecting the resonant light does not induce a modification of the collected signal. The electrical signal generated by the PMT is fed to a lock-in amplifier synchronized with the frequency of a mechanical chopper that chops the laser beam at $f_{\text{chopper}} = 1.2$ kHz. The plasma naturally emits light at the collected wavelength, and using the lock-in amplifier considerably increases the signal-to-noise ratio. After a parametric study, the retained value for the time constant of the lock-in amplifier is $\tau_{\text{lock-in}} = 30$ ms. This time constant being very small compared to τ_{scan} , it offers the best tradeoff with a good filter while ensuring that there is not any distortion of the LIF signal.

IV. ANALYSIS OF THE MEASURED LIF SIGNAL

A. Temperature of the ions

Figure 5 shows measurements performed in the plasma of the PEGASES thruster operating at 200 W of absorbed power and with a mass flow rate of 10 sccm (1.89 mg s^{-1}) of pure molecular iodine. Under these conditions, the operating pressure in the plasma source is 7.5 mTorr (1.17 Pa). The measurement is performed 2 cm downstream the rf coil of

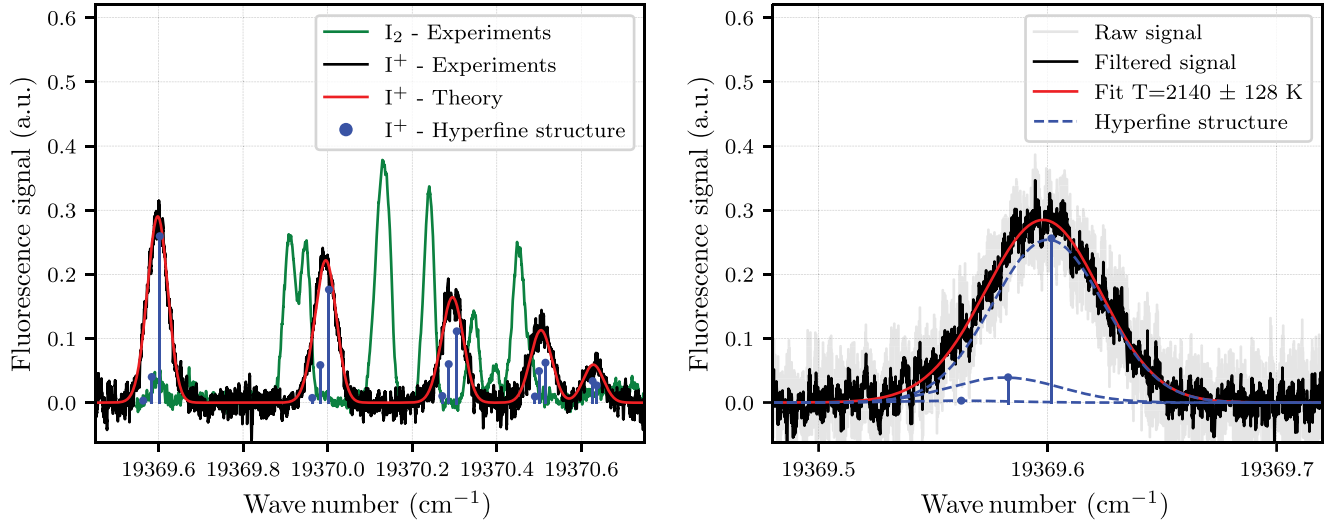


FIG. 5. Left: Experimental LIF profile of the $6s\ ^5S_2 \rightarrow 6p\ ^5P_3$ transition (black) fitted by the theoretical profile (red). The weights and positions of the hyperfine structure are represented in blue. The green solid line is the fluorescence signal of the molecules in a plasma free environment and collected without optical filters. Right: LIF profile in the region centered around $19\,369.6\text{ cm}^{-1}$, restricted to the hyperfine transitions starting from $F = 9/2$. The thruster is operated at a power of 200 W and with a mass flow rate of 10 sccm of I_2 .

the device because it has been shown that the electron density is greater at this location [12]. In Fig. 5, the position and the weights of the hyperfine structure computed with Eqs. (7) and (15), respectively, are represented in blue and the theoretical LIF signal is represented in red. This figure shows that a very good agreement between the theoretical and experimental signals is found when the combination of the center wave number measured by Ashok *et al.* in Ref. [11] and the coupling coefficients measured by Murakawa in Ref. [24] is used. Note that neither the coupling coefficients of Ref. [11] nor the combination of the lower state coefficients of Ref. [11] or [24] with the upper state coefficients of Ref. [9] allow one to fit properly the experimental signal. In the left panel of this figure, the LIF signal of the molecular iodine I_2 is plotted in green. It has been obtained in the facility without plasma (with only pure molecular iodine) with the same experimental setup as that presented above except that the two optical filters were removed to be able to collect the fluorescence that is in the yellow part of the spectra. The superposition of the I^+ and I_2 LIF signals shows that there is not a region where the two fluorescence signals are completely separated. However, for the plasma condition presented in this paper, and more generally in the conditions of electric propulsion plasma sources, iodine molecules are nearly completely dissociated and does not absorb the laser. Two elements confirm this claim. First, the theoretical weights computed with Eq. (15) allow one to perfectly reproduce the whole experimental signal. This would not be the case if the laser were absorbed by the molecules. Second, the analysis of the plasma emission spectra shows that the emission of the ions is dominant compared to the emission of the molecules, confirming the high degree of molecular dissociation for this plasma condition. Nevertheless, the spectrum of I_2 is sufficiently documented [16] to be taken into account if the density of this species cannot be neglected in the plasma.

In order to estimate the temperature of the ions in the plasma, only the part of the signal in the spectral region centered around $19\,369.6\text{ cm}^{-1}$, constituted of the transitions

starting from $F = 9/2$, is considered. First, it is in this region that the signal, constituted of three hyperfine transitions, has the greatest amplitude and, second, the molecular LIF signal being absent from the ionic signal in the region where it should be the most intense (around $19\,370.1\text{ cm}^{-1}$), no molecular absorption is to be expected in this region. The I^+ LIF signal is represented in black in the right panel of Fig. 5, along with a fit of the profile. The temperature of the excited population of ions is $T = 2140 \pm 128\text{ K}$, much greater than that of the atoms [4]. The error of 6% has been estimated as the standard deviation of the temperature measured for seven profiles. The value of the homogeneous broadening [28], fitted from this experimental profile, is $\Delta\nu_H = 14.8\text{ MHz}$, with $\Gamma = 2\pi \times \Delta\nu_H$. It is to be compared to the value of the Doppler broadening $\Delta\nu_D = 1.708\text{ GHz}$. The broadening being mainly inhomogeneous, an additional broadening of the spectral line shape by laser saturation can be neglected with a cw laser. To confirm the aforementioned claim, measurements of the LIF profiles were performed for several values of the laser power by placing optical densities ranging from $\text{OD} = 0.1$ to 0.5 across the laser beam. A linear variation of the intensity of the profiles with the laser power was found, showing that the transition is not saturated. As expected, no modification of the temperature was observed in this range of laser power.

B. Density of the excited state

LIF profiles are measured for several values of iodine pressure at a rf forwarded power of 200 W. This power is chosen to be consistent with former experiments led in Ref. [12]. In this previous work, the electron density n_e , electron temperature T_e , electronegativity α_e , density of the positive species n_+ , and density of negative species n_- were obtained via Langmuir probe and laser induced photodetachment measurements. According to Eq. (14), the integral of the LIF profile is proportional to the density of the lower excited state of the singly ionized iodine, denoted by $n_{\text{I}^+}^*$. The evolution of $n_{\text{I}^+}^*$

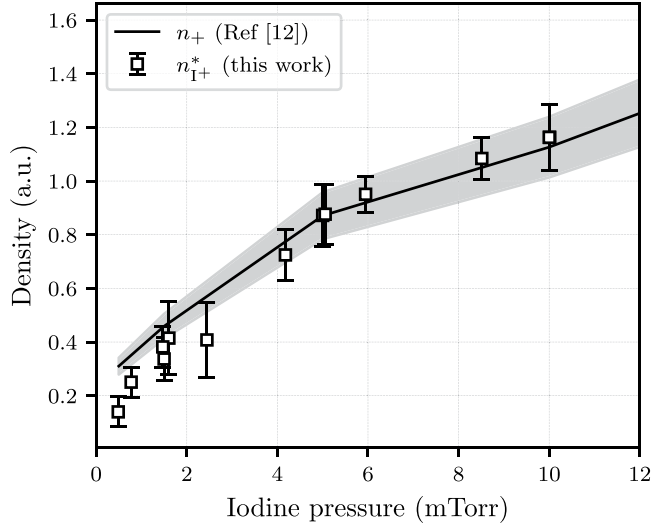


FIG. 6. Evolution with the iodine pressure of the absolute density of positively charged species measured in Ref. [12] (solid line) and the normalized density of the probed excited state of the singly ionized iodine (scattered symbols) measured at $z = 21$ mm. The shaded area represents an uncertainty of $\pm 10\%$. The thruster power is 200 W.

with the iodine pressure is represented, in arbitrary units, with scattered symbols in Fig. 6. Measurements are taken at the location $z = 21$ mm in the source of PEGASES. In this figure, the evolution of the density of positively charged species, measured at the same location in Ref. [12], is represented with a black solid line, the shaded area corresponding to an uncertainty of $\pm 10\%$. Results show that n_{I+}^* and n_+ are proportional. As discussed in Ref. [12], at this location and for this range of plasma conditions, the only charged species present in the plasma are electrons and singly ionized ions. Therefore, it can be concluded from the measurements presented here that the density of the excited state of the singly ionized ions is proportional to the density of the ground state in the range of plasma conditions investigated. Moreover, since absolute densities were measured in the original reference, a multiplicative factor can be multiplied to the measurement n_{I+}^* to obtain the absolute density of the singly ionized ions, denoted by n_{I+} in the remainder of the paper. The good agreement found in Fig. 6 shows that this result is valid in the whole range of pressure investigated. In this range, the electron temperature varies significantly, from 4.5 eV at 0.5 mTorr to 2.5 eV at 15 mTorr.

V. SPATIAL MEASUREMENTS

A. Modification of the experimental setup

In the results presented so far, the direction of propagation of the laser is the x axis (i.e. perpendicular to the axis of the thruster) because of the optimal optical access in this direction. However, in order to perform spatial measurements along the axis of the thruster, LIF profiles are measured with the modified experimental setup represented in Fig. 7. In this configuration, the laser is shot through the vacuum chamber and the exhaust grid of the thruster. Because of the reflective nature of the ceramic backplate of the thruster, the only way

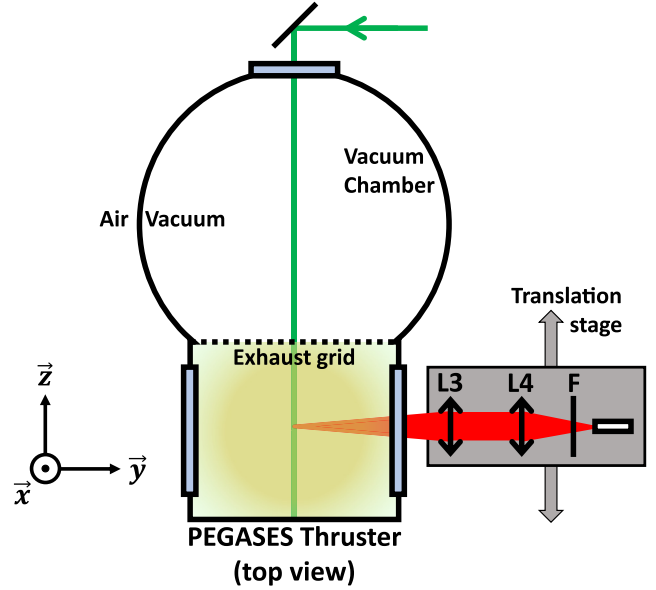


FIG. 7. Schematic of the top view of the experimental setup used to perform spatial LIF measurements.

to get rid of the laser reflection in the collection optics is to use an optical filter around 694 nm to collect the fluorescence of the deexcitation along the transition $2 \rightarrow 3$ (see Fig. 1). As already discussed above, it has been verified that using this collection path does not change the results. In addition, in this configuration the detection system is mounted on a translation stage, which allows one to perform LIF measurements along the z axis, i.e. the thruster axis. Measurements are taken for axial positions comprised between $z = 7$ mm close to the antenna and the maximum value towards the exhaust grid for which an exploitable signal can be obtained.

B. Spatial variation of the measured quantities

One of the main motivations for using LIF in electric propulsion devices is the determination of the ion velocity [30]. If the ions have a velocity component u_i in the direction of propagation of the laser beam, they “observe” a laser frequency that is Doppler shifted and the resonance wave number σ_{mes} is in this case

$$\sigma_{\text{res}} = \sigma_0 \left(1 - \frac{u_i}{c} \right). \quad (16)$$

Spatial profiles of ion temperature, ion velocity, and ion density measured by LIF for three values of iodine pressure for a thruster power of 200 W are represented in Figs. 8(a), 8(b), and 8(c) respectively and discussed below.

First, concerning the temperature, Fig. 8(a) shows that the ions are relatively hot (≥ 1500 K in the whole probed domain). Moreover, a large increase of the temperature is measured close to the thruster antenna for the three pressures investigated, with ion temperatures rising up to 4500 K. This result is not surprising, it can be explained by the acceleration of the electrons in the plasma sheath close to the antenna that heats the ions by collisions.

Second, the evolution of the ion velocity, projected along the axis z of the thruster, is represented in Fig. 8(b). On the one

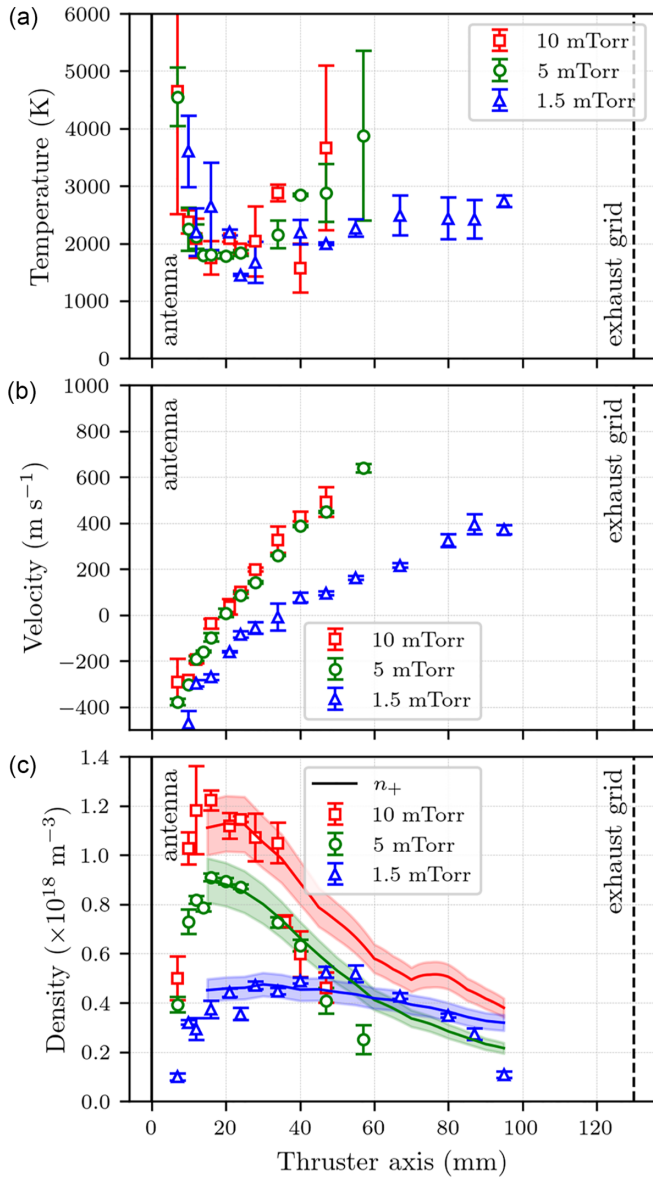


FIG. 8. Spatial evolution of (a) the temperature, (b) the velocity, and (c) the density of the excited state of the iodine ion for three values of iodine pressure. The thruster is operated at 200 W.

hand, the ions have a negative velocity close to the antenna, i.e. they are accelerated backwards. On the other hand, they accelerate out of the thruster towards the exhaust grid. The location for which the ions have a null velocity coincides with the maximum of electron (or ion) density. This observation is coherent with an acceleration of the ions that is due to the ambipolar field that originates from the gradient of electron pressure in the thruster source. This result shows the ability of this setup to measure the velocity of the ions in an electric propulsion device. Moreover, the fact that the probed level is not metastable indicates that the velocity that is measured is precisely the ion velocity at the location of the measurement.

Third, Fig. 8(c) represents the spatial evolution of the ion density, measured by LIF for the three values of iodine pressure. In this figure the spatial evolution of the density

of positively charged species, measured in Ref. [12], is represented with a solid line, and the uncertainty of $\pm 10\%$ is represented with a shaded area. As discussed in Sec. IV B, the data points measured by LIF have been multiplied by the same coefficient as that used in Fig. 6 and represent the absolute value of the singly ionized iodine density n_{I^+} . The comparison of n_{I^+} and n_+ in Fig. 8(c) shows that these two quantities are equal for spatial locations close to the thruster antenna, i.e. $z \leq 30$ nm. However, this equality breaks further in the source, indicating the presence of another charged species. The location at which $n_{I^+} \neq n_+$ is smaller at higher pressures. Particle in cells simulations led in the group [13] that predict doubly charged ions to be present, in the plasma source, particularly at high pressure, in agreement with what is observed in Fig. 8(c).

VI. CONCLUSION

The experiment described in this paper constitutes a measurement of laser induced fluorescence of singly ionized iodine in the plasma of an electric propulsion device. The selected transition used for both the laser excitation and the fluorescence collection is the transition $6s^5S_2^o \rightarrow 6p^5P_3$ at 516.261 nm, which is different from the transitions already investigated in the literature. The theoretical derivation of the weights and positions of the hyperfine lines of this transition showed that a combination of different values of the coupling coefficients available in the literature allows one to perfectly describe the experimental signal. The hyperfine structure is sufficiently split to estimate the ion temperature in the plasma. For the thruster condition of 200 W of absorbed rf power and 10 sccm of iodine (i.e. 1.17 Pa), a temperature $T = 2140 \pm 128$ K (or $k_B T/e = 0.184 \pm 0.011$ eV) has been measured. The transition has been verified not to be saturated, discarding any broadening of the line shape by laser saturation.

In a second part of the paper, a modified optical configuration of the experimental setup is presented and implemented to perform spatial measurements in the whole plasma source along the axis. The temperature, axial velocity, and relative density of the lower level are measured for three conditions of iodine pressure. Results show that this setup is well suited for measurement of the ion velocity in the plasma source. Moreover, the comparison of these data with previous measurements show that the relative density of the excited state of the singly ionized iodine that is measured is proportional to the absolute density of the ground state of this species in the conditions of the experiment. Furthermore, the measurements conducted in this paper highlight the presence of charged iodine molecules I_2^+ in the plasma source at high pressure.

Future investigations will consist in using the PEGASES thruster with a magnetic field to confine the plasma close to the antenna. A dedicated analysis of the Zeeman splitting of the transition will be required to perform this experiment and process the measured signals in magnetized plasmas.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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