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Laser induced fluorescence spectroscopy study of Hall thruster discharge at ignition and warm-up

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Abstract: Hall thrusters have been used and studied since the 1970s, however, the physics governing the transient regime during thruster startup is still poorly known. In this work we investigate the evolution of the atom and ion distribution function along the channel centerline of a low power Hall thruster by means of laser-induced fluorescence spectroscopy in the near-infrared. The temporal evolution of the velocity distribution functions is correlated with the discharge current and thruster temperature changes. We find two main operation modes with mode changes happening either spontaneously or triggered by the operator. We believe these modes to be heavily influenced by the thruster heating up leading to a decrease in electron confinement efficiency.

Nomenclature

I_{sp}	= Specific impulse
E	= Electric field
B	= Magnetic field
$\Delta\nu$	= Change in frequency
ν	= Measured frequency
ν_0	= Transition frequency
c	= Speed of light in vacuum
v_k	= Particle velocity along the laser axis
\vec{k}	= Laser wave vector
\vec{v}	= Particle velocity vector

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I. Introduction

SPACECRAFT electric propulsion (EP) has gained more and more interest in recent decades as space systems manufacturers and researchers strive for higher propellant exhaust velocities, which in turn means higher fuel efficiency and thus lower fuel mass fraction according to the Tsiolkovsky rocket equation.¹ Indeed, exhaust velocities higher than 5000 m/s are unachievable through chemical propulsion, as the energy accelerating the propellant is determined by the chemical reaction used. For electric propulsion however, the energy is supplied externally, it is thus theoretically possible to reach arbitrarily high energy densities. In practice, this is set by the power budget available for propulsion. Given a power input, EP systems have to select between thrust and exhaust velocity, which are the two components of the exhaust power. Hall thrusters (HT) represent a good middle ground with their comparatively high thrust-to-power ratio and moderate specific impulse. Combined with their low volume and long operational life, they have become a prime choice for electric propulsion systems. HTs have been in high demand for applications ranging from attitude control on commercial satellites all the way to the main deep space propulsion system for exploratory probes. Since their adoption in the starlink satellite constellation, they are now by far the most common form of spacecraft electric propulsion. With this growing popularity, the need for a deeper understanding of the physics at play in these thrusters, especially during out of equilibrium regimes, increases. In this work, we investigate the transient regime from discharge ignition to thermal equilibrium through laser induced fluorescence (LIF) spectroscopy, a non intrusive diagnostic that allows us to access the ion and atom velocity distribution.

II. HT physics and functioning

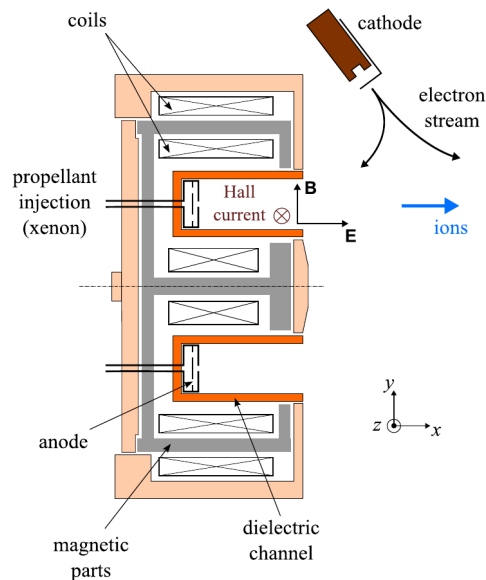


Figure 1: Hall thruster cross-sectional view²

Electric propulsion can usually be divided into two categories: high specific impulse/low thrust and low specific impulse/high thrust. The specific impulse is the impulse delivered per unit of propellant consumed for a given propulsion system. Hall effect thrusters fall into the second category with I_{sp} s ranging typically from 1000 s to 2000 s.³ HETs function by utilizing crossed electric and magnetic fields to ionize and accelerate propellant gas.^{3,4} An external cathode generates electrons which are accelerated towards the anode by the electric field. As seen in Fig. 1, the magnetic field is setup radially, such that the electrons are trapped along the magnetic field lines. This, along with the azimuthal $E \times B$ drift experienced by the electrons results in collision-induced ionization of the propellant gas. This magnetic barrier allows the resulting plasma to sustain an electric field where it is located, thus creating an acceleration region for ions without means of a physical grid contrary to other technologies such as gridded ion engines. The magnetic field strength is

chosen such that electrons are magnetized but ions are not. This allows the ions to be accelerated without being affected by the magnetic field. In the plume, part of the electrons from the cathode are used to neutralize the propelled ions.

III. LIF spectroscopy

Laser induced fluorescence (LIF) spectroscopy is a non-intrusive optical diagnostic technique that allows access to a particle velocity distribution function (VDF) along a specific dimension.

Plasma glow comes from energized particles transitioning to a lower energy level, emitting photons in the process. LIF works by using a laser to induce a chosen transition through absorption rendering it much more common. This in turn greatly increases the occurrence rate of the most probable emission line from the excited energy level to a lower one. When looking at the light spectrum of the plasma at the point where the laser impacts it, the fluorescence line will be Doppler-shifted according to eq. 1. This gives us access not only to the particle's velocity, but to its entire velocity distribution function as the emission spectrum isn't a Dirac but a Gaussian profile.^{2,5}

Table 1 describes the transitions used in this work to probe excited Xenon ion and Xenon atom. Both starting states are metastable and are thus highly populated.

$$\Delta\nu = \nu - \nu_0 = \frac{1}{2\pi} \vec{k} \cdot \vec{v} \quad \text{and} \quad v_k = c \frac{\nu - \nu_0}{\nu} \quad (1)$$

Table 1: Excitation and fluorescence wavelengths of transitions used in this work

Species	Initial level	λ_{exc} (Air) (nm)	λ_{fluo} (Air) (nm)
Xe II	$5d^2F_{7/2}$	834.7227	541.915
Xe I	$6s[3/2]_2^0(1s_5)$	823.1634	823.1634

IV. Experiment setup

A. LIF Bench

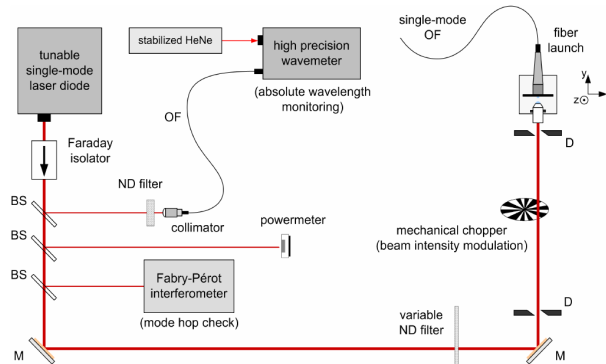


Figure 2: Diagram of the LIF bench at ICARE.

The optical train used for LIF measurements is represented in Fig. 2.² The laser beam, tuned to the wavelength needed to trigger the atomic transition we wish to use, is monitored in wavelength by a wavemeter. A scanning Fabry-Pérot interferometer is used to check for mode hops. As atomic and ionic transitions occur naturally in the plasma all the time and we only want to gather the ones triggered by our laser, we modulate the beam to a chosen frequency by means of a mechanical chopper. On the detection

branch, a lock-in amplifier tuned to the same frequency amplifies only the signal that has the same frequency component: the one generated by our laser.

B. ISCT100 v2

The thruster used in our experiments is the ISCT100v2, which stands for ICARE Small Customizable Thruster 100W version 2. As the name implies, it is a 100 W class Hall thruster developed at ICARE laboratory. It features permanent magnets, a BN-SiO₂ annular discharge channel, a stainless steel ring anode at the back of the discharge channel and a mullite ring to diffuse the propellant gas.⁶ Its main propellant is Xenon gas, but it can also function using Krypton. In our experiments only Xenon was used. The operation point used for this work is described in table 2.

Table 2: Thruster operating parameters

U_{anode}	I_{d}	D_{anode}	D_{cathode}
230 V	$\simeq 0.7$ A	7 sccm Xe	2 sccm Xe

C. Temperature measurements

Temperature measurements have been done on the ISCT100v2 thruster by means of a thermocouple (TC) and optical temperature probes (OP) in order to determine the time it takes for the thruster to reach thermodynamic equilibrium. The optical probes used are the Weidmann Optocon TS2 and TS3. They work by analysing the light sent through a Gallium Arsenide crystal cube as its optical properties change according to temperature. These probes are non conductive, contrary to a thermocouple allowing them to work with better precision in electrically charged environments, however, their measurement range is much more limited (from -200°C to +300°C). Two such experiments have been conducted: the first shown on Fig. 3 was acquired with the thermocouple and one optical probe in contact with the external magnet opposite of the cathode, near the exit plane. It allows us to clearly see the slope changes due to thruster ignition at T+20m and thruster shutdown at around T+80m. The temperature values extracted from the two types of probe aren't the same but the trend is consistent across both methods. The optical probe being non conductive, doesn't register the bumps the thermocouple experiences on thruster ignition and shutdown due to the change in electric field. From this experiment we gather that thermal equilibrium for this thruster is reached at around T+60m since the start of the experiment, so 40 minutes after thruster ignition.

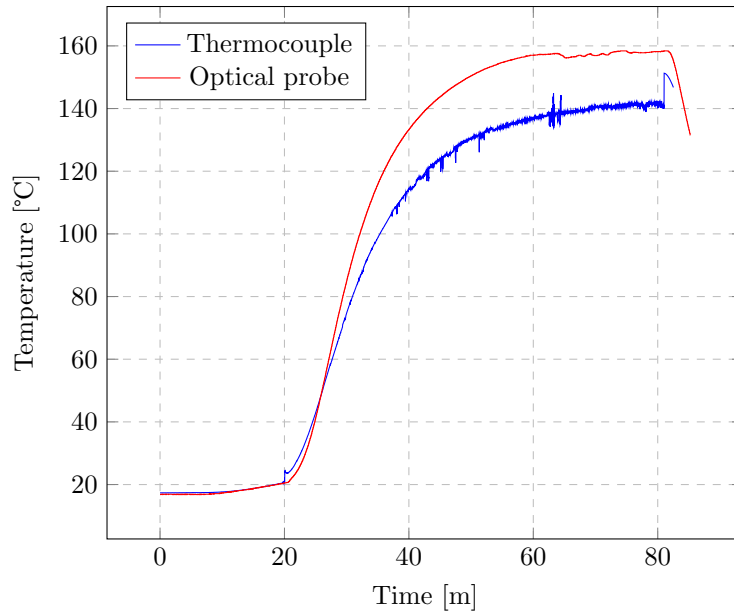


Figure 3: Comparison between OP (red) and TC (blue) readings as a function of time during thruster start

Figure 4 shows the second experiment that was conducted with an additional optical probe situated on the back of the thruster near the gas injection port. For the two sensors on the front of the thruster we observe the same evolution as in Fig. 3 with thruster ignition at around T+8m and thruster shutdown at T+33m. The back probe shows a much slower evolution as it is farther from both the cathode and the plasma.

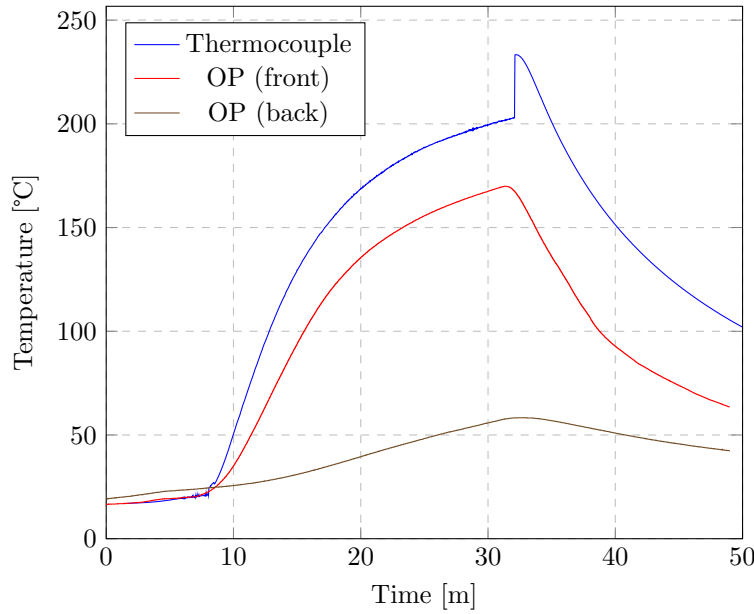


Figure 4: Comparison between TC (blue) and OP (red) at the front of the thruster and another OP (brown) behind the thruster

D. Measurement procedure

In order to study the evolution of particle velocity after thruster discharge ignition, it is critical to operate from a cold start ($> 4h$ since last start). A Hall effect current probe is clamped to the discharge current line

to monitor it during startup as well. From the time the thruster ignites to around T+1h, or when it becomes too unstable, whichever happens first, a LIF spectrum is taken roughly every minute and a discharge current trace every 20 seconds at 100 MS/s for 5ms. The probed region is located in the centerline of the channel, 1 mm from the exit plane (Fig. 5)

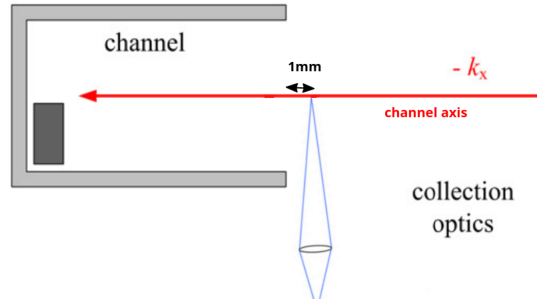


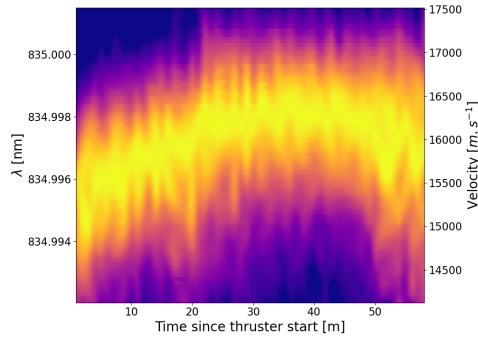
Figure 5: Location of the LIF measurements in the discharge of the ISCT100v2 thruster

Temperature of the thruster was monitored by means of a thermocouple and two optical probes. The thermocouple and one optical probe were placed on a magnet near the exit plane on the side of the thruster opposite of the cathode, while the second optical probe was placed on the back of the thruster.

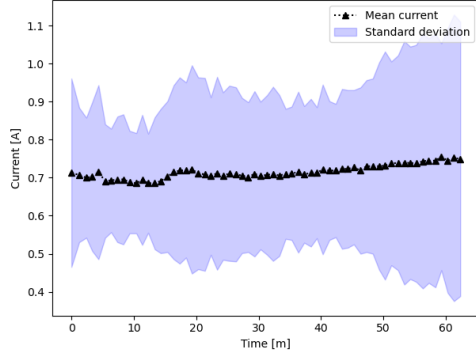
V. Results

A. Ion VDF measurements

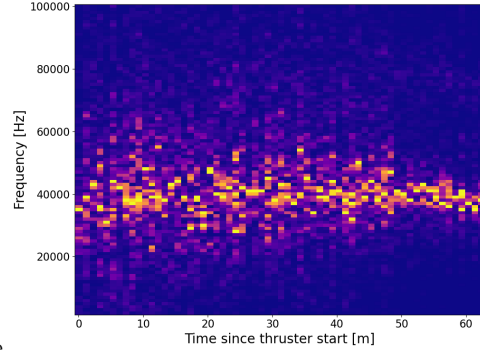
Figure 6a shows a series of Xe^+ LIF spectra recorded after thruster ignition. The ion velocity increases up until T+30m, is stable for around 15 m and then starts decreasing. As for the discharge current (Fig. 6b), the mean is stable at the start before slowly increasing. However, we can also see that the amplitude of the oscillations is increasing at the same time as the exhaust velocity is decreasing. This leads us to believe that there is a correlation between higher amplitude breathing mode⁴ oscillations and lower exhaust velocity. The correlation is further reinforced by analysis of Fig. 6c, which shows the breathing mode oscillation frequency band narrowing implying that not only does the breathing mode oscillations increase in amplitude but they also become more sinusoidal. We think this is due to the increase in thruster temperature (Fig. 3) leading to a widening of the electric field.



(a) Interpolated LIF spectra of Xe^+ ions



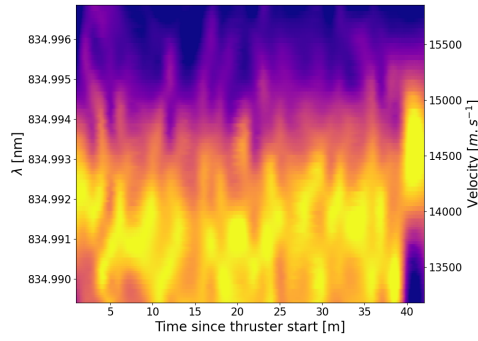
(b) Mean and standard deviation of discharge current



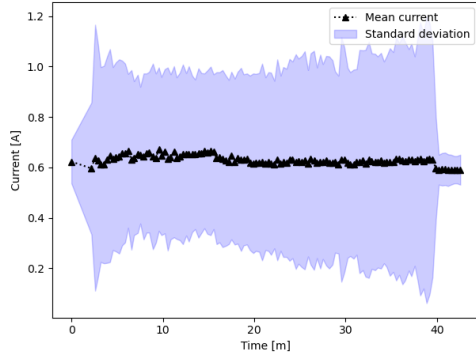
(c) Discharge current spectrum

Figure 6: Thruster start experiment without mode change

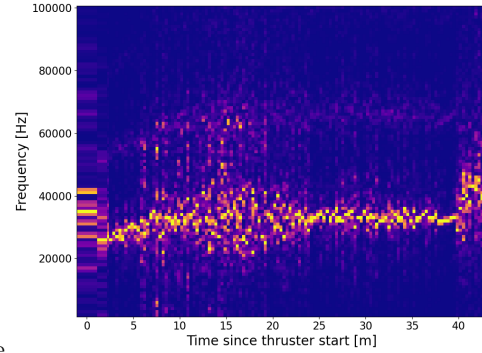
In Fig. 7, we can see that for the first 40 minutes of the experiment the thruster is in a high oscillation amplitude mode (Fig. 7b). This results in a very spread out and unstable velocity distribution (Fig. 7a). By lowering the cathode heating current we were able to induce a mode change to a more stable, lower oscillation mode. This further reinforces our hypothesis that thruster temperature, and in consequence electron confinement, is the cause of this high oscillation mode. Indeed the cathode in our experiment is oversized and quite close to the thruster so the heat it radiates influences thruster operation. It is also possible that the mode change was triggered by lower electron supply due to a lower temperature of the LaB_6 emitter. Spectrum-wise (Fig. 7c), we observe at first the same trend as in the previous experiment (Fig. 6c). As the amplitude of the oscillations increases the frequency components other than the breathing mode oscillations decrease in relative intensity. At $T+40\text{m}$, when the thruster stabilizes, we see them becoming more prominent again as well as an increase in the breathing mode frequency.



(a) Interpolated LIF spectra of Xe^+ ions



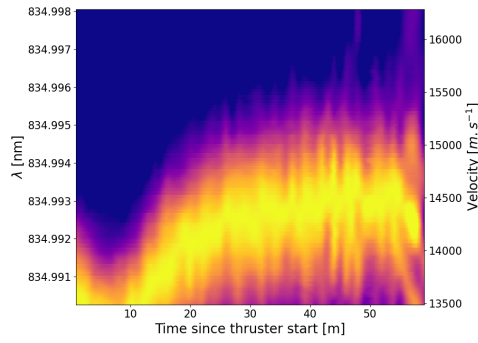
(b) Mean and standard deviation of discharge current



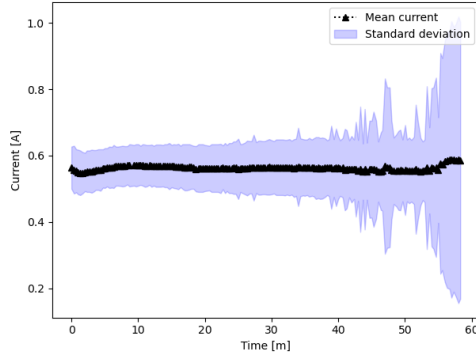
(c) Discharge current spectrum

Figure 7: Thruster start experiment with operator induced mode change

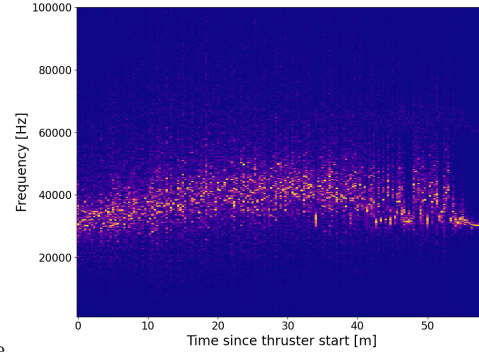
Changes in thruster operation mode can be operator induced but they can also happen spontaneously, as shown in Fig. 8. We can see in the current plot (Fig. 8b) that the thruster is initially in the so-called stable, low amplitude oscillation mode until about T+45m where it starts gradually shifting to the high amplitude mode. On the LIF spectra (Fig. 8a) we can observe that at the very start the ion velocity dips down slightly before climbing up to its stable regime, correlated with a similar evolution on the mean discharge current plot. Given that the anode potential is stable, this means that the thruster is slowly drawing more power as it settles into a stable regime. Then, we see the velocity dipping down at around T+55m. This is correlated to a sharp increase in discharge current oscillation amplitude as can be seen in Fig. 8b. In the same way as the previous experiments, we can see in Fig. 8c that the switch to a higher amplitude oscillation mode is correlated with a lower frequency, better defined breathing mode. The greater discharge instability of this mode caused the thruster to shut down at T+60m.



(a) Interpolated LIF spectra of Xe^+ ions



(b) Mean and standard deviation of discharge current



(c) Discharge current spectrum

Figure 8: Thruster start experiment with spontaneous mode change

B. Atom VDF measurements

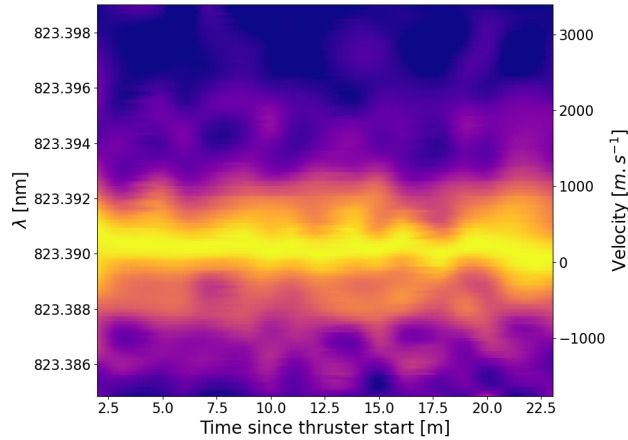


Figure 9: Interpolated Xe Atom LIF spectra

LIF measurements have also been conducted on one atomic transition (Fig. 9). We can see that the atomic velocity distribution is mostly thermal in nature with only a slight bias towards positive velocities mostly due to collisions with ions.

VI. Simulated spectra

While reading the raw LIF spectra allows us to get a rough understanding of the ions' behaviour, we can further increase the precision of our analysis by simulating the lineshape through quantum mechanics, taking into account hyperfine structure of the transition, Zeeman effect, and Doppler broadening. Fitting the obtained lineshape to the experimental lineshape with Doppler shift and temperature as parameters, and using an optimisation loop on Doppler shift allows us to access the noise-free velocity distribution function. We used a preexisting software⁷ and adapted it to fit the needs of this work. Figure 10 shows the results of such a simulation, with smoothed experimental data in black, a simulation with the actual magnetic field strength at the point of measurement in red and a simulation without magnetic field in green. We can see that at such low magnetic field strengths the magnetic field only has a marginal effect on the lineshape, broadening it instead of splitting it into two.

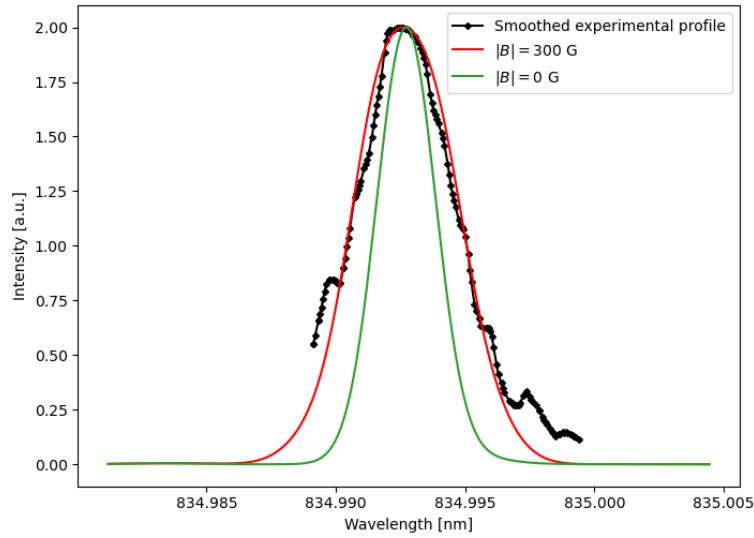


Figure 10: Experimental (black) and simulated lineshapes (red and green) for two magnetic field strengths at T+38m from the same experiment as Fig.8

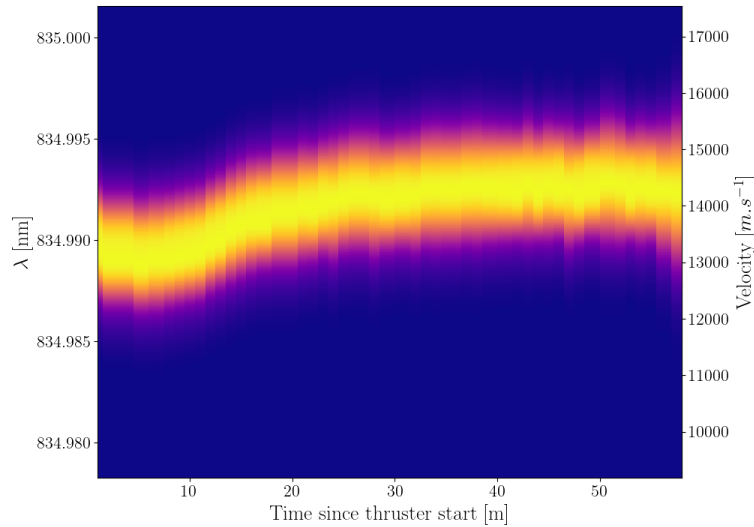


Figure 11: Lineshape simulation spectra from the same experiment as Fig. 8 during thruster start

Doing such a simulation for all of the spectra in an experiment yields Fig. 11, which is the result of simulating the data from the spontaneous mode change experiment (Fig. 8). This allows us to plot the most probable velocity as a function of time since thruster ignition (Fig. 12) and compare it to the velocity of highest fluorescence intensity. We find that both values are very similar in our case, the simulation only improving marginally the smoothness of the velocity curve. Ion temperature determination through this method has been attempted but hasn't yielded satisfactory results thus far.

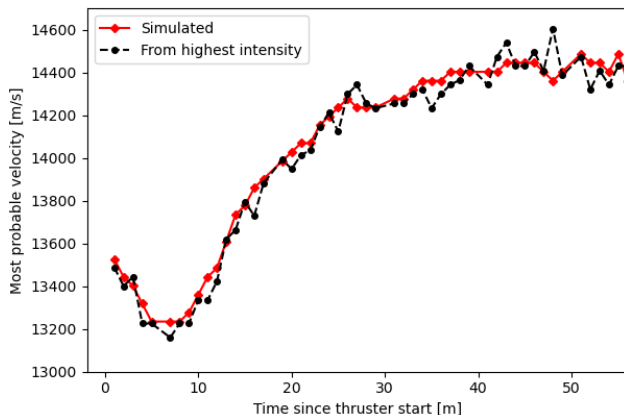


Figure 12: Most probable velocity of ions extracted from lineshape simulation (red) and velocity of highest fluorescence intensity (black) during thruster start (same case as Fig. 8)

VII. Conclusion

We were able to successfully develop a procedure for monitoring the Xenon atoms and ions' behaviour during a hall thruster startup through LIF spectroscopy. This data along with the subsequent lineshape simulations allows us to better understand the physics at work during the establishment of the discharge and the heating up of such a thruster. Coupling the LIF analysis to current measurement allowed us to correlate the changes in exhaust velocity to changes in the mode of the thruster.

More research is still needed to understand the underlying physics governing these modes. The acquisition method described in this paper is limited in temporal resolution (1 LIF spectrum/minute), this is due to the integration time necessary to have an exploitable signal/noise ratio. One way to increase this ratio is to increase the laser power but this is limited by optical saturation phenomenon. As such, using a bigger thruster with a higher ion density would in theory allow us to integrate over a shorter period of time and reach a higher temporal resolution. Such an improvement would allow us to delve into the phenomena happening earlier during thruster startup, resulting in a deeper understanding of the establishment of the discharge.

Acknowledgments

We would like to thank all the other members of the electric propulsion team at ICARE for their help and insight. Alfio E. Vinci, an epteam alumnus, also deserves a mention for his work on the lineshape simulation software. This work wouldn't have been possible without all of them.

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