Diagnostics of Xe Ion in an Anode-layer Type Hall Thruster
Using Laser-Induced Fluorescence

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The discharge oscillation in an anode-layer type Hall thruster is one of the most serious problems to be overcome. In general, a hollow anode is used in order to stabilize the operation. Recent numerical simulation results show the stable operation depends on the ionization rate in the hollow anode. In order to verify the simulation result, it is needed to measure the plasma profile in the hollow anode.

In this paper, as a first step, the number density and the velocity distribution of single-charged xenon ions in an anode-layer type Hall thruster were investigated by means of Laser-Induced Fluorescence (LIF) for the 5dF_{3/2}→6p^2D^o_{5/2} excitation transition at 834.7 nm detecting the non-resonant line to the 6s^2P_{3/2} state at 541.9 nm. As a result, we obtained the relative ion number density and the velocity distributions. The ion velocity distribution function shows both ionization and acceleration occur in the acceleration channel, while only ionization occurs in the hollow anode.

Key Words: Electric Propulsion, Hall Thruster, Laser-Induced Fluorescence, Xe Ion Velocity Distribution

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>:magnetic field</td>
</tr>
<tr>
<td>c</td>
<td>:speed of the light</td>
</tr>
<tr>
<td>D</td>
<td>:hollow anode width</td>
</tr>
<tr>
<td>F</td>
<td>:total angular momentum quantum number</td>
</tr>
<tr>
<td>g</td>
<td>:Lande-factor</td>
</tr>
<tr>
<td>h</td>
<td>:Planck constant</td>
</tr>
<tr>
<td>I</td>
<td>:nuclear moment quantum number</td>
</tr>
<tr>
<td>J</td>
<td>:total electronic moment quantum number</td>
</tr>
<tr>
<td>M</td>
<td>:magnetic quantum number</td>
</tr>
<tr>
<td>P</td>
<td>:relative intensity</td>
</tr>
<tr>
<td>v</td>
<td>:velocity</td>
</tr>
<tr>
<td>(\mu_B)</td>
<td>:Bohr magnetron</td>
</tr>
<tr>
<td>(v_0)</td>
<td>:frequency</td>
</tr>
<tr>
<td>z</td>
<td>:axial position</td>
</tr>
<tr>
<td>Z</td>
<td>:acceleration channel length</td>
</tr>
</tbody>
</table>

Subscripts

0 :static state
i :index

1. Introduction

A Hall thruster is one of the most promising electric propulsion systems for the satellite station keeping or orbit transfer maneuvering because it produces high thrust efficiency with a specific impulse range of 1000 – 3000 s.\(^1\)\(^2\). An anode-layer type Hall thruster has higher thrust density and efficiency than the other type, magnetic layer type Hall thruster. However an anode-layer type Hall thruster also has a serious problem of discharge current oscillation.\(^3\)\(^4\) Therefore, it has never loaded on satellites yet in practical use.

In general, a hollow anode\(^4\) is used in order to stabilize the discharge oscillation. However, even when the hollow anode is used, stable operation range is still narrow. Recent numerical studies\(^5\) show the stable operation depends on the ionization rate in the hollow anode. The purpose of this study is to measure the plasma profile in the hollow anode in order to verify the numerical simulation results. In this paper, the excited ion number density distribution and ion energy function distribution were measured by Laser-Induced fluorescence (LIF) method.

2. Theory

2.1. Laser-induced fluorescence

LIF can be subdivided in two subsequent processes, namely photon absorption and spontaneous emission. Therefore a laser is tuned in frequency over a certain transition frequency and the fluorescence signal is monitored. It has to be taken into account that due to the Doppler effect the absorption frequency of particles moving in the direction of the laser beam is shifted proportional to the relative velocity between the particle and the laser. This shift in frequency is calculated according to

\[
\Delta \nu = \nu_0 \frac{v}{c}
\] (1)
2.2. Hyperfine structure

Naturally occurring xenon consists of nine stable isotopes. The different mass and nuclear charge distribution depending on the number of neutrons leads to slightly different transition energies for the isotopes and thus to a profile splitting into nine lines. Table 1 gives a summary of the natural abundance of the Xe\(^+\) ions and the shift of the line relative to Xe\(^{132}\). Unfortunately experimental data for the isotope shift of the \(5d^2F^27/2 \rightarrow 6p^2D^0_{5/2}\) transition is not available. Following the approach of Manzella\(^9\) and others experimental data of the similar \(5d^4D^27/2 \rightarrow 6p^4F^0_{5/2}\) was used\(^5\)\(^8\).

Further splitting into a hyperfine structure occurs for the isotopes with non-zero nuclear spin, Xe\(^{129}\) and Xe\(^{131}\), due to nucleon-electron spin interaction producing a total of 19 lines. The quantum number that accounts for this effect is the total angular momentum quantum number \(F\) that takes values according to

\[
F = I + J, I + J - 1, \ldots, |I - J|
\]  

(2)

The selection rules state that only transitions with \(\Delta F = \pm 1.0\) are possible with the exception that \(\Delta F = 0\) is not allowed for \(F = 0\). The relative intensity of the isotope shifted transitions can be calculated according to their natural abundance. As for the hyperfine structure, quantum mechanical considerations yield calculation formulas\(^9\) for the relative intensities of the transitions that have to be multiplied with the abundance of the isotope.

In presence of a magnetic field of sufficient strength the Zeeman effect should be considered. It leads to further splitting of the hyperfine structure symmetric to the original lines. The magnetic quantum number \(M\) signifies the projection of \(F\) on the magnetic axis and takes values from

\[
M = -F, -F+1, \ldots, F-1, F
\]  

(3)

The general selection rule is \(\Delta M = \pm 1.0\). Applying this rule for the 9 isotopes of xenon produces a total of 432 lines. The frequency for all these transitions can be calculated according to

\[
\nu = \nu_0 + \mu_0 B g^I M^I g^F M^F \frac{\hbar}{\epsilon}
\]  

(4)

Data for the relative intensities of the Zeeman split lines was taken from the tables provided by Candler\(^9\).

Broadening mechanisms are not separately accounted for since they are overlaid by the line broadening due to the variation in velocity caused by spatial extent of the ionization region.

The resulting line shape is a superposition of 432 transition lines broadened due to the velocity distribution by the Doppler effect. By assuming a suitable velocity distribution function it is possible to reconstruct this complex line shape. For the presented work the function

\[
f(\nu) = \sum_i H(-\vec{\nu}) I_i \nu^2 \exp\left[-\frac{\vec{\nu}^2}{E_0}\right]
\]  

(5)

Table 1: Isotope splitting.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance</th>
<th>Shift in MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe(^{124})</td>
<td>0.096</td>
<td>336.6</td>
</tr>
<tr>
<td>Xe(^{126})</td>
<td>0.09</td>
<td>252.4</td>
</tr>
<tr>
<td>Xe(^{128})</td>
<td>1.92</td>
<td>172</td>
</tr>
<tr>
<td>Xe(^{129})</td>
<td>26.4</td>
<td>113.7</td>
</tr>
<tr>
<td>Xe(^{130})</td>
<td>4.1</td>
<td>83.6</td>
</tr>
<tr>
<td>Xe(^{131})</td>
<td>21.1</td>
<td>16.7</td>
</tr>
<tr>
<td>Xe(^{132})</td>
<td>26.9</td>
<td>0</td>
</tr>
<tr>
<td>Xe(^{134})</td>
<td>10.4</td>
<td>-75.8</td>
</tr>
<tr>
<td>Xe(^{136})</td>
<td>8.9</td>
<td>-140.9</td>
</tr>
</tbody>
</table>

was used, with the abbreviation, as

\[
\vec{\nu} = \nu - \Delta \nu \nu_0
\]  

(6)

Here \(\Delta \nu\) denotes the line shift and \(\nu_0\) and \(E_0\) are fitting parameters. The index \(i\) represents the summation over all 432 hyperfine and Zeeman split components. \(H(-\vec{\nu})\) denotes the Heaviside step function that returns 1 for positive and 0 for negative arguments. It is used to suppress the second arm of the chosen fitting function. The reasons for choosing this function are quite straightforward. It is a well-known fact that skewed velocity distribution functions in which the most probable and the statistical mean velocity differ significantly are characteristic for Hall effect thrusters. Furthermore the discharge voltage constitutes a clear upper limit for the ion energy.

3. Experiment

3.1. Anode-layer type Hall thruster

Figure 1 shows the cross-section of a 1 kW class anode layer type Hall thruster\(^10\). The inner and outer diameters of the acceleration channel are 48 mm and 72 mm, respectively. A solenoid coil is set at the center of the thruster to apply a radial magnetic field in the acceleration channel. The magnetic flux density is varied by changing the coil current. The guard rings are made of stainless steel, which is applied the cathode voltage. It has a hollow anode through which a propellant gas is fed. The width of the hollow anode is 8 mm and the gap between the anode tip and the exit plane of the acceleration channel is 3 mm. Xenon is used as a propellant. A hollow cathode is used as the electron source. A normal operating condition is tabulated in Table 2.

The experiments were conducted in the vacuum chamber of the University of Tokyo with a diameter of 2 meters and a length of 3 meters. The vacuum is achieved by the employment of two rotary pumps (250 l/s), a mechanical booster pump (2800 l/s) and a diffusion pump (3700 l/s).
Table 2. Normal operation parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant Gas</td>
<td>Xenon</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>1.36 mg/s</td>
</tr>
<tr>
<td>Discharge voltage</td>
<td>250 V</td>
</tr>
<tr>
<td>Discharge current</td>
<td>1.1 A</td>
</tr>
<tr>
<td>Applied magnetic field</td>
<td>14 mT</td>
</tr>
<tr>
<td>Back pressure</td>
<td>2.9 x 10^{-3} Pa</td>
</tr>
</tbody>
</table>

Faraday isolator. For the monitoring of the current wavelength emitted by the diode laser a spectrometer was utilized. The fluorescence signal is detected by a collection optic that is movable in the thruster’s axial direction. Through an optical fiber the signal reaches the lock-in amplifier after being filtered by a band pass filter and being converted to an electrical signal by a photomultiplier. An etalon with a free spectral range of 0.75 GHz was deployed as a fine wave meter. For the recording of the signal a digital oscilloscope with a resolution of 10 bit was used.

4. Result and Discussion

4.1. LIF profile

Figure 3 shows one of the obtained line spectra and the result for the fitting function given in equation (5). The good agreement between fitting function and LIF signal attests the general suitability of the function class with its free parameters. Furthermore the detailed consideration of numerous splitting effects provides a solid physical basis for the fitting. Here the Zeeman effect is neglected because the maximum line shifts due to hyperfine splitting are -3.05 GHz and 1.84 GHz. On the other hand the maximum values for the Zeeman splitting are below ±0.4 GHz.

The relative number density can be obtained from the integration of the profile. The velocity distribution function is obtained by deconvoluting the profile using the fitting function.

4.2. Ion number density distribution

Figure 4 shows the relative ion number density distribution in the excitation state. Unfortunately, it is difficult to know the ground state number density from this distribution because electron number density and temperature are functions of axial position \( z \). However, the ionization region shift by the operation parameters, which is the most important information to support the numerical simulation results, was obtained.
4.3. Ion velocity distribution

Figure 5 shows ion velocity distributions. As shown in this figure, the velocity distribution broadening in the acceleration channel is larger than that in the hollow anode. This result indicates that only low energy ions exit in the hollow anode (z<3 mm) because only ionization occurs in this region, while high energy ions also exist in the acceleration channel (z = 0 ~ 3.5 mm), because both ionization and acceleration occur. That is, in this condition, acceleration region locates on the z = 0 ~ 3 mm.

5. Conclusion

The plasma profile in the anode-layer type Hall thruster was investigated. The results are as follows:

1) The fitting function presented in equation (5) is suitable for the estimation of the energy distribution functions of ions since good agreement with the recorded LIF signal can be achieved.
2) We obtained ion number density distributions which are useful data for verification of the future numerical simulation.
3) The ion velocity distribution functions indicate both ionization and acceleration occur in the acceleration channel, while only ionization occurs in the hollow anode.

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