Investigation of excited states populations density of Hall thruster plasma in three dimensions by laser-induced fluorescence spectroscopy

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Abstract. The article deals with investigation of the excited states populations distribution of a low-temperature xenon plasma in the thruster with closed electron drift at 300 W operating conditions were investigated by laser-induced fluorescence (LIF) over the 350–1100 nm range. Seven xenon ions (Xe II) transitions were analyzed, while for neutral atoms (Xe I) just three transitions were explored, since the majority of Xe I emission falls into the ultraviolet or infrared part of the spectrum and are difficult to measure. The necessary spontaneous emission probabilities (Einstein coefficients) were calculated. Measurements of the excited state distribution were made for points (volume of about $12 \text{ mm}^3$) all over the plane perpendicular to thruster axis in four positions on it (5, 10, 50 and 100 mm). Measured LIF signal intensity have differences for each location of researched point (due to anisotropy of thruster plume), however the structure of states populations distribution persisted at plume and is violated at the thruster exit plane and cathode area. Measured distributions show that for describing plasma of Hall thruster one needs to use a multilevel kinetic model, classic model can be used just for far plume region or for specific electron transitions.

1. Introduction
Electrically powered spacecraft propulsions are widely used for space vehicles. However, modern space-programs require thrusters that main characteristics (thrust, specific impulse and life time) must be far beyond currently available ones [1]. Thus research of plasma physical processes is still important.

One of the metrics common used to determine plasma processes and state is distribution of the excited states of atoms and ions. Usually, electron energy-level distributions are taken Boltzmann. For Hall thruster plasma it was shown, that usual assumptions are not correct [2]. So, local thermodynamic equilibrium (LTE) model becomes inadequate for Hall thruster plasma. Accuracy of coronal model and the processes to be taken into account in collisional-radiative model (CRM) should be additionally examined. Moreover, necessity in model of such processes as ionization and excitation from metastable, conversion and transport is open problem. In particular in [3] CRM was suggested for ion and neutral type of the particles. But data in this paper is integral, and question of difference of plasma near the channel and far from it is open. In the work [4] time evolution of the $6s'\{1/2\}1-6p'[3/2]2$ (834.68 nm) excited neutral xenon population density was measured for different thruster operating conditions. And was shown...
that the theoretical calculation base on CRM and experimental values were at good agreement. However the work was made just for neutral atoms and for one thruster area.

The aim of this paper is a study of xenon atom and ions excited state population density (ESPD) of Hall thruster plasma with high spatial resolution to different thruster region. Also consideration of additional processes that should be taken into account to increase model accuracy. Laser induced fluorescence method was chosen for it.

2. Theory
Laser-induced fluorescence (LIF) can be modeled as two separate processes. First one is selective populating of high energy level during radiation absorption. The second one is fluorescence, emission, which occurs when electron moves to a level with lower energy.

Let us describe three level system figure 1. Electrons amount on \( j \)-th level will be \( N_j \). Adding laser with fixed wavelength get redistribution of populations between levels having energy difference that matche to transition. In multilevel kinetic model the system of equations described balance between occupation densities of all particles species could be written as

\[
dN_j/dt = \sum_q \left( N_j\omega_{qj} - N_q\omega_{jq} \right) + \sum_q S_{jq} + Tr_j, \tag{1}
\]

where \( \omega \) is frequency of collisional and radiative transitions, \( S_{jq} \) is a particles source function (responsible for particles transformation) and \( Tr_j \) is a transport coefficient, \( q \) is the number of examined energy levels. The first coefficient responses for level transitions, the second one for particles species change-over and the last for transport. Analytical solution of this system of equations is the rather complex task and is a subject of future research, while approximated one can be achieved with the following assumptions. Time of laser influence on the system is 5–10 ns, the value of cross sections of electrons with Xe nucleus (having max values amount processes involved) in Hall thruster is approximately \( 10^{19} \) \( \text{cm}^2 \) \[5\], so we assume, that during laser pulse the main process affecting on a level populations are radiative.
For system in figure 1 with laser influence equations can be written as
\[
dN_j/dt = N_i B_{ij} \rho - N_j \left( B_{ij} \rho - \sum_{i<j} A_{ji} \right),
\]
(2)
in stationary case, when laser power can be assumed constant:
\[
N_i^l = \frac{N_i}{B_{ij} \rho} \left( B_{ij} \rho - \sum A_{ji} \right).
\]
(3)
In equation (3) and hereinafter the summation be carried out for \( j < i \). On the other hand, intensity of the light emitted by one of the transitions (fluorescence signal) depends of the excited state population and can be written as
\[
dI = k N_j A_{ji} h c \Omega/4\pi,
\]
(4)
where \( N_j \) is amount of particles with electron at \( j \) level, \( A_{ji} \) is spontaneous emission probabilities for chosen transition, \( h \) is Planck constant, \( \lambda \) is wave length of detected radiation, \( \Omega \) is solid angle of receiving radiation, \( k \) is normalization constant.

From equation (3) and equation (4) we got
\[
N_i^l = \frac{4\pi I_{jk} \lambda}{k A_{jk} h c \Omega B_{ij} \rho} \left( B_{ij} \rho - \sum A_{ji} \right).
\]
(5)
Within the described assumptions: \( N_\Sigma = N_i^l + N_j^l = N_i + N_j \). For levels with inner quantum number less than or equal to 6, excited state population density can be resolved from equation for statistical weight [6]:
\[
\frac{N_i}{N_j} = \frac{g_i}{g_j}.
\]
(6)
So, for second state population density \( N_j \) could be write as follows:
\[
N_j = \frac{N \sum g_j}{g_i + g_j} = \left[ \frac{4\pi I_{jk}}{k A_{jk} h c \Omega B_{ij} \rho} \left( B_{ij} \rho - \sum A_{ji} \right) + g_j \right] (g_i + g_j)^{-1}.
\]
(7)
It should be mentioned that excited state population density (ESPD) achieved with described method are relative to the total particles density for given point in the volume, and this total values are not homogeneous across the volume.

3. Equipment and diagnostic facility
The measurement was obtained on laboratory model of Hall effect thruster (figure 2). It produces low-temperature moving xenon plasma with mean parameters: electron temperature 10–100 eV, ion concentration about \( 10^{11} \text{ cm}^{-3} \), electron concentration (in plume) about \( 10^{11} \text{ cm}^{-3} \), neutrals concentration about \( 10^{12} \text{ cm}^{-3} \), Debye radius \( 10^{-5}–10^{-6} \text{ mm} \), ion velocity about 20 km/s.

3.1. Vacuum system
Experiments are performed in the vacuum test facility TMVC11 (figure 3). The TMVC11 is a horizontal vacuum chamber with a 1.8 m diameter and 4.5 m length (volume 11 m³) made of non-magnetic stainless steel. It is equipped with viewing and measuring windows.

The evacuation system consists of low and medium vacuum station Pfeiffer Combi-Line WH 950 P with dry compressing screw pump HeptaDry 200 P and Roots pump Okta 1000. High vacuum achieved with eight turbopumps Pfeiffer HiPace 2300 with pumping speeds of up to 15200 l/s for \( N_2 \). The TMVC11 is fully-automatic system that controlled with LabView. The residual pressure is approximately \( 2 \times 10^{-7} \text{ mbar} \), and the pressure during thruster operation at 1.2 mg/s anode mass flow rate, is approximately \( 8 \times 10^{-5} \text{ mbar} \), corrected for xenon. Facility pressure is controlled by two hot-cathode ionization gauges.
3.2. Experimental setup
The detecting spectroscopic stand is equipped of optic system, laser system, control system, and detection system figure 4. The laser system used in this experiment is the Nd: YAG pulsed laser with the wave length wide 192–2600 nm and with the output pulse energy from 1 to 400 mJ (depends of wavelength). Impulse duration is 5–9 ns. The OS consist of various optical elements used to change the laser beam parameters and to deliver it in vacuum chamber. The radiation is collected by objective placed in vacuum chamber and collimated into the fiber, then the signal pass through the monochromator (M266) or interference filters and get into multialkali photomultiplier tube connected to an oscilloscope.

The objective is located on spatial 6-depths-of-field parallel mechanism with six identical kinematic chains of “hexapod” type, that allows scanning of the plume. The location of axes during the measurements is demonstrated in figure 4. The data are obtained for volume 12 mm$^3$ in 2 mm increments. For control laser parameters was used power meter. The laser spectral width liberal exceeds the spectral lines. The measurements are carried out in a saturation regime so the measured laser power instability produces deviations less than 5%.

4. Results
Hall thrusters usually use xenon as a propellant, so singly ionized xenon (Xe II), and neutral atoms (Xe I) are dominant species. Xe I and Xe II has the following ground states: $5p^6$ $^1S_0$ and $5s^25p^52p_{3/2}^0$ with wavelengths less than 200 nm what makes ground states not useful for LIF diagnostics [7]. More appropriate choice is to use metastable states.

4.1. Xe I
Strong transitions of Xe I are in ultraviolet and infrared range that makes difficult for detection. In this work was considered LIF signal from two common resonant transitions 823.16 nm $6s[3/2]_2$ $\rightarrow$ $6p[3/2]_2$ and 828.011 nm $6s[3/2]_1$ $\rightarrow$ $6p[1/2]_0$ [8]. Also a new 3-level scheme with
Figure 3. Overall view of the TMVC11.

pumping at 450.097 nm $6s[3/2]^2 \rightarrow 6p'[1/2]_1$ detection at 764.2 nm was investigated. The results of the experiment show that the ratio of the excited state population density depending on location at thruster plume changes within the margin of error figure 5.

In other words the ESPD of Xe I is comparatively homogeneous for different thruster region (plume or near the thruster face). On basis of ESPD profile of Xe I concentration was calculated by means of simple CRM (3–4 levels) [3]. The results for different transitions are similar and its shape are presented in figure 6.

4.2. Xe II
The levels with energies from 12 eV to 16 eV were examined. Partial Grotrian diagram of Xe II is shown in figure 7. The all transitions are written in table 1.

Among multitude of investigated energy-level scheme the operational ones are that pumped from 5$d$ series. It can be explained that the interaction between $5s5p^6$ and the $5s^25p^4nd$ series is very strong and a big part of ions obtained in exited $5d$ state. In view of live time ($10^{-8}$–$10^{-6}$ s), and metastable ionization cross section (equal approximately $10^{-19}$ cm$^2$) [5], so one needs to take account of step ionization processes.

In the other hand the LIF signal could not be detected from the energy-level schemes with pumping at the metastable $6p$ group or $6s[3/2]^2$ state. If one takes into account that schemes was made right in terms of levels energy configurations, then there are two explanation of LIF signal absence:
Figure 4. Scheme of diagnostics setup: optic system (OS), control system (CS), photomultiplier tube (PMT) and detection system (DS) and top view of the thruster.

Figure 5. The space distribution ($x$–$z$) of the ratio of $6p[3/2]_2$ to $6p'[1/2]_1$ Xe I population for distance along thruster axis $y$ equal 5 and 100 mm.

(i) no particles are at pumping level, however that disprove by emission spectrum;
(ii) the deexcitation processes without emission occur faster than spontaneous emission.

So at our operation conditions the main depopulation of this excited states happens through additional excitation to the upper states. We were able to mark out 3 type of Xe II ESPD profiles along axis $x$ (figure 4) depending on transitions figure 8. In general ESP sharply rise at the borders of thruster channel and get its maximum in the thruster center. That connected with high particles concentrations at this regions. The small shift aside of the cathode persist to all transitions. The population of learning states at the cathode area near the thruster channel for some transitions (484.433, 541.9 and 487.65 nm) have strongly pronounced peak while at another transitions (529.2, 492.15 and 453.2 nm) it is feebly marked. For distance more 5 cm the pike disappear for all transitions. That indicates a different term sensitivity to electron process.
Figure 6. The Xe I concentration (in standard unit) space distribution obtained for simplified CRM for 764.2 nm transition.

Table 1. The considered transitions, energy levels and wavelengths.

| Wavelength (nm) | Configuration |
|----------------|---------------|
| 1 547.26 → 484.433 | 5d2[3]7/2 → 6p2[3]7/2 → 6s2[2]5/2 |
| 2 680.574 → 492.15 | 5d2[3]7/2 → 6p2[2]5/2 → 6s2[2]3/2 |
| 3 605.1 → 529.2 | 5d2[4]7/2 → 6p2[2]5/2 → 6s2[2]3/2 |
| 4 834.724 → 541.9 | 5d2[4]7/2 → 6p2[3]5/2 → 6s2[2]3/2 |
| 5 659.5 → 487.65 | 5d2[4]9/2 → 6p2[3]7/2 → 6s2[2]5/2 |

and to accuracy of a definitions constant of a process balance. The better group of transition to concentrations analyzing is: 529.2, 492.15 and 453.2 nm.

For better visualization the space distribution of ESPD ratio were calculated and are shown in figure 9. The results display that for all transitions distributions of ESPD differ from each other at the thruster exit plane and cathode area. It could points on a formation of the double charge ions, on a presence of heavy particle collisions and on total electrons activity near thruster face. Also the foundation of molecular ions could be. Maximal difference was measured for 6p2[3]7/2 to 6p2[2]5/2 more than 10 times and minimum for 6p2[2]5/2 to 6s2[2]5/2 just 4 times figure 10. The Xe II concentration profile was calculated (by simplified CRM 4 levels and process: electron ionizations or recombination, excitations or deexcitations and radiation at assumption of optically thin plasma). The results of two different transitions 529 and 542 nm near the exit
Figure 7. Partial Grotrian diagram of Xe II.

Figure 8. Three main types of Xe II ESPD profiles along axis $x$ depending on transitions. Different colours correspond to various $y$-locations: 5, 10, 50 and 100 mm.

plane and in far region are demonstrated in figure 11. For corrected model this distribution should be equal, in our case they are similar just for plume area.

4.3. Errors of the approximations
As for the same Xe II energy levels there are several transitions. The population of one level was founded for different schemes ($6p^2[3]^3/2$ or $6p^2[4]^1/2$). The ratio of their value along axis $x$ is shown in figure 12. As follows from graphs the deviations are less than 20%.
**Figure 9.** The space distribution ($x$–$z$) of the ratio of $6p^2[^3]S_{5/2}$ to $6p^2[^2]S_{5/2}$ Xe II population for distance along thruster axis $y$ equal 5, 10, 50 and 100 mm.

**Figure 10.** The space distribution ($x$–$z$) of the ratio of different excited states Xe II population for distance along thruster axis $y$ equal 5 and 100 mm.
Figure 11. The Xe II concentration (in standard unit) space distribution (x–z) obtained for simplified CRM (see text) for 541.9 and 529.2 nm transitions.

Figure 12. The ratio of the population found by different schemes 547.26 → 484.433 nm and 699.088 → 484.433 nm along axis x at the thruster center for y equal 5 and 10 mm.

5. Conclusion
In the present work, the method for determination of level population by LIF was suggested and tested. The excited state population density of HT was measured in 3D by LIF. The observed errors were within 20%. Seven ion transitions and three transitions of neutral atoms have been explored. Neutral atoms ESP distribution is comparatively homogeneous for different thruster region and can be described by using one plasma model CRM. Ions ESP distributions are not uniform at cathode area and near the thruster face. Models for plasma at these regions should be based on multi-level kinetic equations, where processes included in equations should be chosen experimentally. It is worth consider formation of the double charge ions, a step ionization, a presence of heavy particle collisions and possible for some transitions a foundation of molecular ions.
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