Plasma Diagnostics on Xenon for Application to Ion Thrusters

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Plasma diagnostic investigations on xenon are presented to be applied to the plasma produced by a radio frequency ion thruster. At a cold gas cell, two-photon laser-induced fluorescence on neutral xenon was used to determine a calibration function for the LIF system. A microwave-generated plasma was investigated with emission spectroscopy, Fabry-Perot interferometry and Langmuir probes to characterize the plasma state. Electron densities in the order of $10^{18} \text{m}^{-3}$ and distributions of the electron temperature between 20000 K and 60000 K were found. These quantities are in the same dimensions as those expected in the discharge chamber of the ion thruster yielding the conclusion that similar evaluation methods can be applied for the ion thruster characterization. The RIT-10 ion thruster was installed to a vacuum tank and successfully operated. First emission spectroscopic measurements were carried out.

I. Introduction

At the Institute of Space Systems (IRS) of the University of Stuttgart, non-intrusive diagnostic methods have been under investigation for plasma thrusters as well as for reentry plasmas since more than a decade. Recently, a test stand was prepared for ion thruster testing to be used with an RIT-thruster from EADS-ST for plasma diagnostic investigation of the plume and the plasma properties close to the grids. Ion thrusters have attracted the attention of satellite manufacturers for a long time because of their high specific impulse and efficiency. For physical reasons, one of the most promising propellants is xenon. The investigation of local characteristics of the xenon plasma by means of non-intrusive methods is a very important task for understanding the processes in these thrusters. For this purpose, spectroscopic techniques for the ion thruster plume investigations are currently under development at IRS. Two-photon laser-induced-fluorescence for density measurements on neutral xenon has already been performed in a cold gas cell.

Emission spectroscopy, electrostatic probes and Fabry-Perot interferometry are used for preliminary measurements in a xenon plasma produced by a microwave generator. The emission spectroscopic measurements showed a strong non-equilibrium situation in the plasma. Although only weak ion emission could be detected, the electrostatic probe measurements showed electron densities in the order of $10^{18} \text{m}^{-3}$ and distributions of the electron temperature between 20000 K and 60000 K. Because the electron density is one of the key parameter in the discharge, measurements of the cut-off density using a diagnostic microwave (8GHz to 12GHz) were used to validate and confirm the Langmuir probe data. Fabry-Perot interferometry measurements were carried out to determine the Doppler temperature of the plasma yielding values between 2000 K and 3000 K. For this purpose, the

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hyperfine structure of the emission lines under investigation had to be resolved and simulated. The results of the hyperfine structure splitting are in good agreement with experiments on an SPT thruster in France.  

In addition, a Corona-type equilibrium has been modeled, using results from the described measurements and excellent consistence could be derived by comparison with emission spectra. Although the microwave plasma is substantially different from the ion thruster plume, particularly in terms of pressure, the properties of the charged particles determined in this investigation are in the same regime as those reported for the plasma state in the discharge chamber of ion thrusters. Therefore, the results from the microwave-generated plasma indicate a successful application to the ion thruster plasma.  

In a next step, two-photon laser-induced fluorescence for density measurements as already carried out in the cold gas cell will be performed at the microwave generated plasma and finally be applied to the ion thruster plume. Furthermore, a possible extension of the laser-based measurements to ionized xenon will be investigated.

II. Two-photon laser-induced fluorescence on neutral xenon in a cold gas cell

For the development of the LIF technique and for the determination of a calibration technique, experiments were carried out with a cold gas cell. Figure 1 shows the scheme for the experimental set up for LIF and a picture of the calibration cell.  

The 450nm output of a Lambda Physik SCANmate 2E Dye Laser, which is pumped by the XeCl field 201 eximer laser at 308nm, is frequency-doubled to generate 225.4 nm laser pulses of approximately 15 ns duration and 2mJ energy with a repetition rate of up to 50 Hz. The laser output is varied over 0.001 nm. The scanning and the synchronized data collection are computer controlled. The synchronized data collection is realized with the help of a boxcar, which works as data integrator and simultaneously controls the photo multiplier Hamamatsu R636-10 which was used for fluorescence detection.

1,3 -lens systems, 2 - the gas cell

Figure 1. Scheme of the LIF experimental set-up and picture of the cold gas cell.
The 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005

Due to the high excitation energy of xenon, the absorption process requires two photons for the excitation. Dependent on the gas pressure, quenching processes cause additional depopulation of the excited level and have to be taken into account in the rate model. Figure 2 describes the excitation scheme with the fluorescence transitions and the rate model used for evaluation.

By fitting the fluorescence decay at different pressure levels, shown exemplarily in Fig. 3 for a gas pressure of 0.21 mbar, effective lifetimes could be determined and the natural lifetime was obtained from a Stern Volmer plot to ~93 ns by the intersection with the axis of the inverse effective lifetime as shown in Fig. 4.

Although the fluorescence data at low pressures showed large errors due to oscillations caused by disturbances of the photo multiplier signals by the eximer laser discharge, the results are within the range of the lifetimes between 75 and 218 ns reported in literature. Recently the pumping laser has been replaced by a NdYAG laser which provides a smaller pulse duration at almost the same pulse energy; these disturbances are expected to be eliminated. The experiments will be repeated with the new laser system as soon as possible.

Figure 2. Two-photon excitation scheme with fluorescence transitions in the VIS-NIR wavelength range and rate model involved in the analysis.

Figure 3. Fitting of the fluorescence decay at 0.21 mbar with the effective lifetime 22 ns.
Figure 4. The Stern-Volmer plot of fluorescence for a two-photon excitation at 225.4 nm.

From the rate model, the relation between fluorescence emission and neutral gas density is given by:

\[ N_{hv} = A_{ik} \int N_2(t) dt = N_0 \frac{A_k}{A+Q} \int \phi^2(r,t) dt = N_0 \frac{A_k}{A+Q} \int I_0^2(r,t) \frac{1}{(hv)^2} dt \]

To obtain a calibration function to eliminate the only inaccurately known excitation cross sections and the laser profile, the measured fluorescence data has been fitted by a function given by

\[ S_f = k \cdot g \cdot N_0 \cdot \frac{A_k}{A+Q} \frac{1}{(hv)^2} \int I_0^2(r,t) = \xi \cdot \frac{1}{A+Q} \cdot N_0 \]

where \( \xi \) is a constant. The values for the quenching contribution \( (A+Q)^{-1} \) can be found from the lifetime measurements for density levels between \( 10^{18} \) and \( 6 \times 10^{20} \) 1/m³ to: \( A+Q(N) = 6.53 \cdot 10^{-13} \cdot N + 1.07 \cdot 10^7 \). The measured dependency of the fluorescence signal on the population density is shown in Fig. 5 where the peak values of the wavelength scans at different pressure levels inside the calibration cell are plotted over the particle density. Therefore, the measurement data were approximated by the function \( F(N) = \frac{\xi}{6.53 \cdot 10^{-13} \cdot N_o + 1.07 \cdot 10^7} \cdot N_o \), with the calibration factor \( \xi = 14.79 \cdot 10^{14} \cdot \frac{S \cdot m^3}{V} \).

Figure 5. Dependence of the fluorescence signal on the population density.

The 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005
III. Characterization of the microwave plasma

A microwave generator with a SAIREM downstream source was used to generate stable plasma. The magnetron microwave generator produces a maximum power of 300 W at a frequency of 2.45 GHz. At these power levels, the wave guide resonator of the SAIREM system requires water cooling. The quartz crystal glass pipe with a diameter of 50 mm, in which the plasma is generated, is mounted perpendicular to the axis of the downstream source through an appropriate hole, with brass flanges that stick out of the waveguide for 50 mm. Attached to the 300 mm-long glass tube were aluminium flanges at each side. One end was connected to the turbo pump which allows a minimum pressure of $3 \times 10^{-6}$ mbar to be achieved. On the other end of the glass tube the gas was injected perpendicularly to the tube axis to allow an axial view of the plasma through a Suprasil quartz window with 30 mm in diameter. A flow controller with a maximum flow of 13 SCCM controlled the xenon mass flow into the discharge tube. In addition, the flow controller acted as a valve. The leakage rate was determined to be $10^{-4}$ mbar·l/s. The partial pressure of air due to the above leakage rate for a given working pressure was 1 % at 1 mbar and 1 ‰ at 0.1 mbar. 25 different operating conditions were investigated with a variation of power in the range between 100W and 300W and of pressure between $7 \times 10^{-2}$ mbar and $2 \times 10^{-1}$ mbar. For the Langmuir probe measurements, the upstream flange carried a duct with either double or single probes which could be rotated and shifted to measure different radial and axial positions. The emission spectroscopic measurements as well as the Fabry-Perot measurements were conducted at a position 50 mm downstream from the wave guide resonator axis where maximal electron densities were obtained from the double probe measurements. For the Fabry-Perot measurements, the plasma emission was focused on an optical fiber by a spherical mirror with a focal length of 500 mm to be fed into a Burleigh interferometer. The light is expanded through a lens system to a collimated beam with a diameter of 22 mm and after passing the semi-permeable coplanar mirrors (reflectivity 94 %) of the FPI cavity, it is focused (f=200 mm) to the entrance slit (d=0.2 mm) of the following spectrometer (Jobin Yvon HR320; grating 1200 lines mm). At its exit slit a photomultiplier (Hamamatsu R928) detects the light, resolved by the FPI. Emission spectroscopic measurements have been performed at the same position, using a focusing mirror with a focal length of 125 mm, an Acton 2750 spectrometer with a focal length of 750 mm an a Thompson CCD camera with 512x512 pixels of 20µmx20µm size. A 50 lines/mm grating was used for the detection of overview spectra between 400 nm and 1000 nm yielding a pixel resolution of 0.4 nm which turned out to be sufficient for an investigation of the excitation temperature and a comparison with simulated spectra. Figure 6 illustrates the set-up for emission spectroscopy and Langmuir probe measurements; Fig. 7 shows the set-up for the Fabry Perot measurements and a picture of the microwave generator in operation.

![Experimental set-up for emission spectroscopy and Langmuir measurements.](image)

**Figure 6.** Experimental set-up for emission spectroscopy and Langmuir measurements.
Figure 7. Optical set-up for Fabry-Perot interferometry and microwave generator in operation.

A. Langmuir probe results

The double Langmuir probe (DLP) measurements yielded spatial profiles of electron density and electron temperature. The almost radially flat density distribution showed densities in the order of $10^{12} \text{ cm}^{-3}$ with a maximum of $3 \times 10^{12} \text{ cm}^{-3}$. The axial distributions show the maximum density ~50 mm off the downstream source axis. However, at some discharge conditions, a weak increase of the electron density towards the outer radial regions in the range of $8 \times 10^{11} \text{ cm}^{-3}$ to $2 \times 10^{12} \text{ cm}^{-3}$ could be observed. The radial electron temperature shows a strong decay of a factor 2 to 4 towards the plasma axis at $r=0$ mm. The highest measured temperature levels were seen in the range of $6 \times 10^{4} \text{ K}$, close to $r=18 / a=0$. In axial direction towards $a=75$ mm, much lower temperatures of $2 \times 10^{4} \text{ K}$ were detected. In order to confirm the electrostatic probe measurements, the microwave transmission experiment showed cut-off densities with a lower limit of $2.4 \times 10^{12} \text{ cm}^{-3}$ which are in good agreement with the results extracted from DLP measurements.

In addition, single probe measurements were conducted to determine the electron energy distribution function (EEDF) which was necessary for the interpretation of the emission spectroscopic data. It was found that the electrons do not behave according to a Maxwellian energy distribution function. Instead, the measured distribution function in the region of interest (3eV to 14eV) could be described by a one-parameter fit described by Behringer 14. This distribution indicated that the main processes are caused by inelastic interactions in contrast to the general elastic behavior, predicted by the Maxwell distribution. Furthermore, an electronic beam with a narrow energy distribution probably caused by the microwave absorption was identified with energies up to 20 eV close to the wall of the glass tube 8.

B. Results from Fabry Perot interferometry

The Fabry Perot interferometer acts as a high-resolution monochromator. From the Doppler broadening, the heavy particle temperature is determined. For xenon, the isotope shift due to the different masses of the nine stable isotopes and the hyperfine structure due to non-zero nuclear spins of two isotopes ($^{129}$Xe and $^{131}$Xe) have to be taken into account yielding a total of 21 single lines for one electronic transition. Both effects are of the same order and have therefore to be considered. The magnetic field in the plasma and hence the Zeeman effect can be neglected. The isotope shift has been treated comprehensively in literature, and data for the field shift (FS) and the normal (NMS) and specific mass shift (SMS) have been taken from 14. The frequency shift of a transition $i$ between two isotopes with the masses $A, A0$, respectively, can be calculated as:

$$
\delta \nu_{i}^{AA'} = \delta \nu_{i,FS}^{AA'} + \delta \nu_{i,NMS}^{AA'} + \delta \nu_{i,SMS}^{AA'}
$$
Because the nuclear spin of $^{131}$Xe (I=3/2) is > 1, not only the electrical dipole interaction as for $^{129}$Xe (I=1/2) has to be considered but also the electrical quadrupole interaction. The hyperfine (HF) effect does not split the energy levels of the fine structure into more sublevels but shifts them towards different energies. In the absence of a magnetic field, each HF-level is 2F +1-times degenerated, if F is the quantum number for the total angular momentum ($F=F+I$). The energy of the hyperfine structure levels is calculated using

$$E_{HFS} = E_{Dip}(I, J, F) + E_{Quad}(I, J, F) = \frac{C}{2}A + \frac{B}{4} \frac{3C(C+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}.$$  

C is hereby a shortcut for $C = F(F+1) - J(J+1) - I(I+1)$. A and B are the hyperfine constants and have been taken from $^{16}$. For a complete simulation the line strengths have to be determined as well. They obey their statistical weights and can be calculated as written in $^{17}$. Table 1 shows the isotope shifts, their natural abundances and the necessary data for the hyperfine structure calculation of $^{131}$Xe and $^{129}$Xe.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Isotope Shift (MHz)</th>
<th>Natural Abundance (%)</th>
<th>Line Strength</th>
<th>(\Delta E) (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{131}$Xe</td>
<td>$I = \frac{3}{2}; J = \frac{5}{2}$</td>
<td>3.5</td>
<td>3.5</td>
<td>0.343</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$I = \frac{1}{2}; J = \frac{3}{2}$</td>
<td>2.5</td>
<td>2.5</td>
<td>0.057</td>
</tr>
</tbody>
</table>

After determining the different intensities, the lines have been broadened with a Lorentzian profile for the apparatus broadening (0.6 pm) and a Gaussian profile for the Doppler broadening. The best fit between measured and simulated profile yields the heavy particle temperature. Figure 8 shows a comparison between measured and theoretically calculated line profile for the observed transition of neutral xenon at a wavelength of 823.16 nm. 21 components of this spectrum are indicated with Dirac delta peaks, 3 times enlarged. For the different operating conditions, Doppler temperatures between 1900 K and 2600 K were observed.
C. Results from emission spectroscopy

Emission spectroscopic measurements were taken in a wavelength range between 400 nm and 1000 nm with a pixel resolution of 0.4 nm. All measurements were wavelength calibrated using the emission of a mercury lamp and intensity calibrated to spectral radiance using a calibrated ribbon band lamp. In general, only weak emission of ionized xenon could be detected and the spectrum was dominated by the emission of neutral xenon. Figure 9 shows emission spectra measured at different pressure levels with an identification of the radiating levels.8

Figure 9. Measured xenon spectra at different pressure levels.

An evaluation of the spectra assuming a Boltzmann distribution of the excited levels yielded excitation temperatures in the range of 2500 K, but the intensities showed a rather large deviation from the Boltzmann plot. Therefore, a Boltzmann distribution cannot be assumed and a Corona model was developed for the interpretation of the measured spectra. In the Corona model, excitation occurs by collisions with electrons and de-excitation by radiation. In the rate equation for the excited level density, cascade transitions yielding population by radiative transitions from higher levels must be taken into account. The measured electron densities and EEDFs were used to model the excitation.8 Finally, the emission of each level under consideration can be calculated from:

$$\varepsilon(\lambda) = \frac{1}{4\pi} \frac{hc}{\lambda} \left( \frac{p-n_e kT}{kT_H} - n_e \right) \sum_{\ell=0}^1 A_{\ell,m} \int \frac{2E}{m_e n_e + n_g} \left[ n_0 f_0(E) + n_B f_B(E) \right] dE$$

Here, pressure, electron temperature, electron density, heavy particle temperature and electron energy distribution function are measured with independent methods and the Einstein transition coefficients were taken from literature. In order to calculate the excitation cross section due to collision, a theoretical approach was used, as no complete set of experimental data in the pressure range of interest is yet published. The two different EEDFs in the above-mentioned equation (f0, fB) indicate the bulk distribution (v) and the distribution due to the beam (B), caused by the microwave. Figure 10 shows a comparison of measured and simulated spectra. Taking into account that both emission spectra and Fabry-Perot data were measured as an integration along the line of sight and
electron density, temperature and EEDF result from separate measurements, the agreement between simulation and measurement is excellent. Therefore, the Corona model is well-suited for the plasma states under investigation.

Figure 10. Comparison of a measured xenon spectrum with a simulation using the Corona model.

IV. Vacuum system and thruster

For operation of the ion thruster, one vacuum tank was equipped with an additional oil diffusion pump system to achieve sufficient vacuum quality for ion thruster operation. The system consists of two oil diffusion pumps with a pumping speed of 50000 l/min. Minimal pressures of $1.6 \times 10^{-6}$ mbar without gas flow and $3 \times 10^{-5}$ mbar in operation with a mass flow of 4 SCCM xenon were achieved. The thruster is operated in grounded mode, only for start up, a glowing wire is used for electron generation. Figure 11 shows a picture of the RIT-10 before start up and with the thruster in operation. So far, only first tests have been performed where different operating conditions were studied.

Figure 11. Vacuum tank with RIT-10 mounted and target and RIT-10 in operation.

Figure 12 shows emission spectra taken in the plume of the RIT-10. Since plasma emission is rather weak, the spectra were taken in full vertical binning mode of the camera with a slit width of 50 µm and an acquisition time of 10 s. Still, the dark current of the CCD camera was very high. In further experiments, a more sensitive camera with...
enhanced cooling will be used. No further information than the visibility of both neutral and ion emission lines in
the plume region have been obtained from these spectra since no defined operating condition was fixed in this first
test.

Figure 12. Preliminary emission spectrum taken during the first test at IRS in the plume of the RIT-10.

V. Conclusion and further plans

Plasmdiagnostic measurements on xenon for future application to ion thrusters have been conducted. For
neutral xenon, a calibration function could be obtained using a cold gas cell. Due to oscillations probably caused by
the pumping laser discharge, the accuracy of the lifetime data in the low-pressure range is rather low. To improve
the accuracy, the system has been extended by an NdYAG pumping laser. The measurements will be repeated with
the new system as soon as possible.

A microwave-generated xenon plasma has been
investigated with emission spectroscopic measurements,
Fabry Perot interferometry and electrostatic single and
double probes. Heavy particle temperatures have been
determined between 1900 K and 2600 K from the Doppler
width of a neutral xenon line at 823.16 nm taking the hyper
fine structure and the isotope shift of xenon into account.
Electron temperatures and electron densities have been
measured with electrostatic double probes in a radial
distribution between 20000 K and 60000 K and between
8·10^{11} \text{cm}^{-3} \text{cm}^{-3} and 2·10^{12} \text{cm}^{-3}, respectively. The electron
densities have been verified independently by microwave
absorption measurements and one-dimensional FDTD-
simulations. These values are in rather good agreement with estimations of the conditions in the discharge chamber of an
ion thruster as shown in Fig. 13. Therefore, the measurement
methods as well as the data evaluation applied to the
microwave plasma are regarded as well-suited for plasma
diagnostics in the discharge chamber of the ion thrusters as
well.

Emission spectroscopic measurements have been performed in the wavelength range between 400 nm and
1000 nm with a pixel resolution of 0.4 nm. The interpretation of the spectra showed that no Boltzmann distribution
of the excited states could be assumed. Therefore, a Corona model has been developed and applied, based on the
plasma parameters determined by the above mentioned methods in combination with electron energy distribution
functions which have been extracted from measurements with electrostatic single probes. The comparison of
measured and simulated spectra showed very good agreement.

The ion thruster test stand was successfully operated with minimal pressures down to 10^{-6} \text{mbar} without gas flow
and 3 \text{10}^{-5} \text{mbar} with the RIT-10 in operation. In a first test, emission spectra have been measured in the plume.

Figure 13. Plasma conditions in the
discharge chamber of an ion thruster

The 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005
Further testing for a characterisation of the plume plasma is foreseen as soon as possible. Further future goals are an application of the two-photon LIF technique on neutral xenon to the RIT plasma as well as the investigation of a possible three-photon excitation of ionized xenon.

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