OPTICAL SPECTROSCOPY ANALYSIS OF A STATIONARY PLASMA THRUSTER

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Abstract

The Xenon plasma of the stationary plasma thruster prototype SPT M2 has been analysed by means of Optical Emission Spectroscopy (OES). XeI, XeII and XeIII emission lines have been identified in the spectral range from 230 to 630 nm and used to determine excitation temperature for these three species. We conclude that excited levels are far from Local Thermodynamic Equilibrium. Intensity ratio of XeII to XeI lines are used to try to establish correlations with SPT performances against the discharge voltage and the Xenon flow rate. In the near UV range (230-300 nm), impurity lines are clearly identified. Some of them (BI) result from the erosion of the dielectric channel of the SPT and could be used to monitor this erosion which remains an important technical problem.

Introduction

The stationary plasma thruster SPT M2 has been analysed in SEP laboratories by Optical Emission Spectroscopy (OES). The purpose of this investigation is to provide non intrusive diagnostics to estimate some of the basic plasma parameters such as the excitation temperature, the degree of ionisation, the ratio of doubly to singly ionised ions, the density of metastable atoms and the presence of impurity atoms.

It has been performed during the long duration tests of SPT M2 Model A5 without any interferences with the test program, under a financement from the CNES (Centre National d’Etude Spatiale).

Description of the experiment

The thruster and the vacuum facility have been described previously [1, 2]. The base pressure is of the order of 2.10^-7 mbar.

The figure 1 is a sketch of the vacuum chamber showing the position of the SPT. The chamber pressure is about 3.10^-5 mbar when the thruster is operating at his nominal flow rate.
Figure 2 is a schematic cutaway of the AS model.

The light emitted by the SPT plasma is collected along the three directions shown on figure 2. For each channel, a 15 mm diameter lens focuses the light to the end of a 5 m-long optical fiber. The other end of which is outside the vacuum chamber at the entrance slit of a monochromator. Each lens is protected by a cylindrical shield in aluminum alloy in order to avoid as much as possible the material deposition on the surface of the lens. The shield and the diameter of the lens define a cylindrical observed volume of about 15 mm diameter.

In direction 1, the light is collected from a region slightly inside the dielectric thruster channel. In direction 2, the light is collected at about 1 cm from the exit plane of the SPT and perpendicularly to it. Direction 3 intersects the SPT axis at 20 cm from the exit plane so the light is collected only from the plasma beam outside the discharge region.

The emission spectra are recorded between 390 and 630 nm with a JOBIN YVON HRP monochromator. The focal length is 60 cm and the resolution of the order of 0.1 nm.

High resolution spectra are also recorded by means of a 125 cm focal length monochromator. The resolution is 0.01 nm and the spectral range is extended in the UV region to a wavelength of 230 nm and in the near infra-red to 830 nm. The observation is made through a fluorine window at the wall of the vacuum chamber. The whole SPT discharge can be seen from this window with an angle of 45°.

The photo-multipliers used are RCA 7265 which has a good sensitivity in the visible and RCA 31034 equipped with a GaAs photo-cathode for its sensitivity from the near UV to the near infra-red.

**Experimental results**

**Systematic thruster configurations analysis between 390 and 520 nm**

A systematic spectral analysis has been performed in the wavelength range 390 to 520 nm at moderate resolution (0.1 nm), for 5 thrusters configurations. For each thruster configuration several experimental conditions are tested such as those represented in the diagram of figure 3. The discharge voltage can be varied between 250 V and 450 V and the xenon flow rate between 3 and 6 mg/s. Thus the spectra have been recorded under 32 different experimental conditions.

The light intensity along direction 1 is higher than along direction 2 and the spectra are almost identical. So only direction 1 is used.

One hundred and three Xenon lines are observed in this spectral range. Most of them correspond to Xe I and Xe II and a few ones to Xe III. Figure 4 gives an example of the emission spectrum between 390 and 410 nm. Some impurity lines are also observed permitting the identification of Iron, Nickel and Aluminium. Iron and Nickel are obviously the result of sputtering of the stainless steel chamber walls. The presence of Aluminium is more surprising as the only aluminium parts are the shields of the lenses which are placed outside the plasma beam.
The lines identification and the physical constants are derived from the tabulated data.\textsuperscript{3, 4, 5}

The number densities of Xenon excited states deduced from the spectral lines intensities, divided by the statistical weights of the upper levels, have been plotted in arbitrary units versus the state energy for XeI and XeII for each experimental conditions.

Figure 5 is an example of the Boltzmann plot for XeI, XeII, XeIII. It corresponds to the A54 configuration which has been retained for the long duration test\textsuperscript{61}. For this configuration only, the spectral range has been extended between 390 to 630 nm.

Due to the limited energy range for XeI lines, it is difficult to define an excitation temperature for this system. Excitation temperatures of XeII values between 9000 and 15000°K can be inferred from Fig. 5 for XeII.

This method was applied for testing various thruster configurations. Despite the fact that from one configuration to another important variations of intensities for a given line are observed, no significant changes result for the corresponding Boltzmann diagram.

Another method for testing the efficiency of the various configurations is to use the intensity ratio for lines of XeI, XeII and XeIII and to try to establish correlations in these ratios with experimental parameters such as discharge voltage and xenon flow rate.

No systematic influence of the discharge voltage can be established. However it happens that some variation of the ratio of XeII to XeI line intensities can be correlated to the flow rate variation and that an optimum seems to exist for flow rate between 5 and 5.5 mg/s as can be seen in Fig. 6.

The ratio of XeII and XeIII excited state densities have been determined using the experimental line intensity ratio. Let us denote by j and k the upper levels of two XeII and XeIII lines and $\tau_j$ and $\tau_k$ their respective radiative lifetimes. If we assume that the decay of the two levels is mainly radiative, the ratio of the reduced densities of XeII and XeIII excited states is expressed as:

$$\frac{[\text{XeIII}^*]}{[\text{XeII}^*]} = \frac{N_k}{g_k} \cdot \frac{\tau_j}{\tau_k} / \frac{N_j}{g_j}$$

The determination of this ratio has been done using the 422.3 nm (7s$^1$2D$_{5/2}$ -> 6p$^2$P$_{3/2}$) XeII line and the 392.25 nm (6p$^3$P$_2$ -> 5s$^3$S$_2$). The typical values for the [XeIII]/[XeII] ratio are in the range 0.09-0.15. Note that these lines have nearly equal excitation energies. In the absence of further indications for the pathways in which the emitting states are populated (directly or not from their respective ground states), this result must be considered as only indicative of the respective importance of Xe$^+$ and Xe$^{++}$ densities in the plasma.
Metastable atoms density measurements

Metastable atoms populations are important as probable intermediate steps in the ionisation process of the SPT discharge. The measurement of metastable atoms concentrations is possible under certain conditions by absorption and using a spectral lamp of the same gas as an external source. A preliminary experiment has been performed in a 2.4 GHz discharge operated in Xenon at a pressure of 20 mTorr.

The absorption is measured in a 10 cm long plasma column on the transitions 6s(3/2), -- > 6p(3/2), and 6s(3/2), -- > 6p(3/2), at 840.9 nm and 823.2 nm respectively. The concentration derived for the probed level 6s(3/2), is of the order of $3 \times 10^{10}$ cm$^{-3}$ in this microwave plasma.

The same kind of measurement has been attempted, so far without success, across the SPT plasma beam at 1 cm from the exit plane. This failure is due to technical difficulties and it does not preclude the feasibility of this measurement.

Spectral analysis at high resolution

A more detailed analysis has been undertaken during the endurance test of the final thruster configuration A54. The spectral range explored extends between 230 and 830 nm.

The figure 7 shows part of the spectrum recorded between 230 and 300 nm under high resolution, collecting light from the SPT through the fluorine window. A total of 40 Xenon lines are observed. All known Xenon lines are detected. Lines corresponding without ambiguity to Iron, Nickel, Aluminium, Boron and Carbon are also observed.

The detection of the UV boron lines is of practical interest as it might be used for monitoring the erosion of the dielectric channel. Carbon is detected for the first time because of the newly installed SEPcarb (r) tiles in the vacuum chamber as a beam target. A Boltzmann diagram could not be drawn for the numerous XeIII lines due to the lack of physical data for XeIII in the UV.

Spectral analysis of the plasma beam

This analysis has been performed during the endurance test at moderated resolution (0.1 nm). The light is collected along direction 3 (see figure 5). The spectrum is shown in figure 8. The 40 lines are identified as corresponding to XeI and XeII except one unidentified line at 472.7 nm. Lines corresponding to XeII are the more intense ones.

The Boltzmann diagram has been plotted (Fig.10), but for the same reasons explained before, it is very difficult to determine a temperature from this diagram. We can only determine the temperature to lie between 6100 and 13500 K. The beam is not thermalised at 20 cm of the exit of the thruster. Despite the fact that the temperature is lower than the temperature in the thruster channel.

Discussion and conclusion

From the experimental results relative to spectral line intensities of XeI, XeII and
XeIII, it may be concluded that the plasma is far from Local Thermodynamic Equilibrium (LTE). This results from the physical situation in which the frequency for electronic excitation exchanges between excited states is much lower than typical radiative decay frequencies.

In order to interpret the experimental results, it would be necessary to build a Collisional Radiative Model (CRM). This task is made difficult, first by the complexity of Xel, XeII and XeIII energy level schemes, second, by the need to know electron excitation cross-sections between individual states and third, by the need to use a realistic Electron Energy Distribution Function (EEDF). The difficulty relative to cross-sections can be partly overcome at least for Xel using the large body of works published on the modelling of Xe-based excimer lasers. Semi-empirical cross-sections could be used for electronically induced transitions between Xel excited levels and for XeII and XeIII excited states. Concerning the problem of EEDF two distincts approaches could be used. The first one is to use the results of numerical particle transport simulation which has been undertaken in CPT (Centre de Physique Théorique) Palaiseau. The second one is to use some assumptions for the EEDF like that recommended by the Russian group of MIREA which assumes that the EEDF can be considered as the sum of two Maxwellian groups (a cold and a hot one) and a group of primary electrons the energy of which depends on the local potential. [8]

References


Fig. 1. Sketch of the vacuum chamber, the position of the SPT is indicated.

Fig. 2. Cutaway of the SPT with directions for the collection of light.

Fig. 3. A5 thrust versus voltage and flow rate.

Fig. 4. SPT p-wave spectrum between 300 and 1.1 MHz.

Fig. 5. Boltzmann diagram for XeI, XeII and XeIII.

Fig. 6. XeI intensity ratio versus flow rate for various configurations.
Fig. 7.

Fig. 8. Visible spectrum of the beam of the A54 thruster.

Fig. 9. Boltzmann diagram for XeII lines in the beam of the A54 thruster.