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Investigating the plasma properties of a Xe-microplasma thruster

R Seton\textsuperscript{1,2}, P Sturesson\textsuperscript{1,2,3} and A Persson\textsuperscript{1,2}

\textsuperscript{1} Ångström Space Technology Centre, Dept. of Engineering Sciences, Uppsala University, Uppsala, Sweden

\textsuperscript{2} Div. of Microsystem Technology, Dept. of Engineering Sciences, Uppsala University, Uppsala, Sweden

\textsuperscript{3} Dept. of Military Sciences, Swedish Defence University, Stockholm, Sweden

ragnar.seton@angstrom.uu.se

Abstract. By combining optical emission spectroscopy (OES) and Langmuir probes, the plasma properties of a Xenon-microplasma thruster have been investigated. Using IV-curve analysis the properties of the plasma have been determined and correlated to the power fed into it. Satisfactory agreement has been obtained with the results of OES measurements (line-ratio technique) and shock-cell distance calculations. While the fuel consumption of the thruster decreased very linearly with the power fed to the plasma, the plasma properties was found to have behave in a more complex way. In the studied power range, the density ratio between at least two ions, with upper configurations 5p^5(\textsuperscript{2}P_\textsuperscript{3}3/2)7p and 5p^5(\textsuperscript{2}P_\textsuperscript{3}3/2)6p, strongly indicated that the ionization processes of the former was favourable in terms of thrust for the geometry of the nozzle. This was supported electron temperature measurements from IV-curves.

1. Introduction

Macroscale plasma thrusters are currently being developed for upper stage propulsion of cargo and even manned missions [1]. One of the main challenges still facing these new propulsion systems is the large power consumption of the plasma sources. As fabrication costs for smaller satellites such as cubesats keep dropping, plasma-based microthrusters have started to gain interest and are showing promising results compared to their traditional, resistively heated counterparts.

At the Ångström Space Technology Centre (ÄSTC) micropropulsion systems have been developed since its inception almost 20 years ago [2]. In this paper, we have investigated the properties of a miniaturized, split-ring resonator-based Xe-microplasma thruster intended for micro- and nanosatellite propulsion. Here, the relation between plasma, mass \( w \), and exhaust plume properties have been studied using Langmuir probes, microscopy, and optical emission spectroscopy (OSE) in order to determine how plasma properties such as ion population and electron temperature effect the heating of the gas.

2. Device Fabrication and Characterization

The microthruster investigated in this study was based on a newly developed design, intended not just for plasma propulsion, but also to compare the efficacy of the microplasma source to other, conventional resistive heaters [3]. The source itself was based on a stripline split-ring resonator
An adjustment was made to the original design, removing the waveguide and placing the RF-feed connection directly on the split-ring, see figures 1 and 2a, matching the 50 \( \Omega \) impedance with the angle of the connector.

The chip was fabricated using 150 \( \mu \)m thick High-Temperature Co-fired Ceramics (HTCC) alumina green tape sheets (ESL 44007-150G, ESL, USA), onto which electric conductors were screen printed with platinum paste (ESL 5574-A, ESL, USA). The sheets were stacked in modules and the gas inlet was created using a 1.1 mm spiral drill. Drilling from left to right in figure 1, the SSRR gap was created together with the hole over which the bond wire, that later formed the Langmuir probes, was mounted. The nozzle module was drilled separately, first all the way through with a 200 \( \mu \)m drill, then partly again with the 1.1 mm drill to a depth of 250 \( \mu \)m to form a conic stagnation chamber. The same drill was then used to form a diverging nozzle exit. After mounting the platinum bond wire the modules were laminated and sintered at 1550°C. Following the sintering the gas inlet had a diameter of 900 \( \mu \)m, the nozzle throat 165 \( \mu \)m, and the exit hole 330 \( \mu \)m.

Before mounting the UMC connectors, the chip was inspected using X-ray (XTV 130, Nikon, Japan), figure 2a, to ensure the layers were aligned correctly. After mounting the connectors the resonance of the plasma source was characterized with a vector network analyzer (Fieldfox 9912, Agilent, USA) showing a resonance frequency of 2.5 GHz. Finally the Langmuir probes were created by fusing the bond wire as described in ref. [5], by running a 3 A current at 25 V through it.

### 3. Method

The fundamental properties of both the plasma and the thruster were evaluated with increasing RF-power fed to the microplasma source from a custom-made RF source, described in ref. [4]. In these measurements, the gas inlet of the device was connected to a Xe reservoir at a pressure of 60 kPa. The mass flow through the inlet was measured with a Xe calibrated mass flow sensor (AWM3000V, Honeywell, USA). The thruster was then placed inside a vacuum chamber which was pumped to a pressure of 52 Pa. At each power, an IV-curve of the plasma inside the thruster, and an optical emission spectrum and a micrograph of the exhaust plume outside the thruster were recorded as described below. A total of 8 power levels were investigated in this way, ranging from 0.31 W to 0.81 W.
3.1. IV-curves
Several plasma properties important for a thruster can be determined using Langmuir probes, assuming unmagnetized, collisionless conditions, as described in ref. [6]. In our double probe setup, each probe was connected to a source meter unit (2400 SourceMeter, Keithley, USA) that biased one of them between -20 V and 40 V, and measured the current to the other, as shown in figures 3a and 3b.

Figure 2. X-ray image (left) of one of the finished device before fusing the bond wire to produce Langmuir probes. The $S_{11}$ curve (right) of the imaged chip showing a resonance frequency of 2.5 GHz.

Figure 3. Recorded IV-curves with plasma parameter linear fits showing a comparison of low and high powered plasma IV-curves (right), and selected regions for curve fitting to determine plasma parameters (left).
To avoid charging and heating effects, these sweeps were divided into 100 equidistant discrete steps, each with a dwell time of 4 ms, which were visited randomly.

3.2. Emission Spectra
With the plasma source mounted in the vacuum chamber, the spectral emission of the exhaust was collected with a reflective collimator (RC01SMA-P01, Thorlabs, USA) mounted on a sight glass. The collimator was connected directly to the spectrometer (CCS200, Thorlabs, USA), recording each spectrum with an integration time of 20 s. With a spectral accuracy of just less than 2 nm, at full width at half maximum (FWHM) at 630 nm, the setup did not offer the possibility of analyzing spectral line broadening. Instead, intensity ratios of known lines were used to determine and verify several of the same plasma parameters as extracted from the IV-curves. The properties of the lines selected and shown in figures 4a and 4b have been investigated in ref. [7] and are available in the National Institute of Standards and Technology's (NIST) Atomic Spectra Database (ADB) [8].

3.3. Microscopy
When the Xe gas was expelled through the circle symmetric nozzle, a standing wave pattern became visible in exhaust plume, as shown in figure 5. While the distance between each shock cell in the plume is simply the wavelength of this standing wave, the distance from the nozzle exit to the first cell, \(d_0\), is directly related to the nozzle pressure and thereby to the thrust of the rocket [9].

Images of the plume were captured using a stereomicroscope (SMZ800, Nikon, Japan) camera (DS-2Mv, Nikon, Japan) through the same sight glass as the spectra. After correcting for the angle of the camera, the known size of the nozzle exit was used as reference to calculate \(d_0\).
4. Results and discussion

The ion density ratio can give information about different ionization processes in the plasma. In figure 4b, the intensity of the four most prominent lines with known Einstein A-coefficients in the visible spectrum are shown. Of these the two lines with the same lower level configuration, $5p_6^5(^2P^o_3/2)6s$ and with the largest $\Delta E$ are those with upper level configurations $5p_7^5(^2P^o_3/2)7p$ ($\lambda_{7p}=480.70$ nm, given by ref. [8]) and $5p_6^5(^2P^o_3/2)6p$ ($\lambda_{6p}=840.92$ nm, from ref. [8] as well).

Their relative population density can be calculated by:

$$\frac{N_{7p}}{N_{6p}} = \frac{l_{6p}A_{6s\rightarrow 6p}}{l_{7p}A_{6s\rightarrow 7p}}$$

where $N_k$ are the density of ions in the upper state, $I_k$ the line intensities and $A_{6s\rightarrow k}$ the Einstein A-coefficient for the transitions, for $k \in \{6p, 7p\}$. The results are shown in figure 6 and indicate an increasing amount of the more energetic ion towards lower powers. However, the noise in the spectra was also more prominent at lower powers making the signal-to-noise (SNR) ratio worse in this regime. Still, these results indicate more complex ionization processes that may affect the thruster's performance.

This was further supported by the analysis of the IV-curves, see ref. [6]. Figures 6 and 7, show the estimated ion densities and electron temperatures from these calculations. Both show local maxima in the region as the emission spectra inferred the most $5p_6^5(^2P^o_3/2)7p$ ions.

The mass flow measurements, shown in figure 8, indicated that these processes seem to have a lesser impact on the fuel consumption of the thruster as the mass flow decreased linearly with power. On the other hand, the dependency of the shock cell geometry on the supplied power, figure 9, was more complex and showed a reduced thrust as the lower energy ions started to dominate the plasma, despite the power increase.
5. Conclusion

We demonstrate that the plasma properties of a Xe-microplasma thruster can be analyzed with both non-invasive methods - OES - and integrated sensors - Langmuir probes. The results show that the plasma characteristics depend on the plasma power in a rather complex way, e.g. by promoting at least two different ionization processes in the investigated power range. These could be inferred from both the Langmuir probe measurements and from the spectrum, and were found to affect the thrust characteristics, where \(5p^{3}(2^3P^0_{3/2})7p\) ions appeared to contribute most effectively to the thrust increase. The fuel consumption, on the other hand, was found to have a less complex and more linear dependence in the studied range. Still, our results show that it is important to monitor the plasma in order to create a well behaved microplasma thruster, and that ways of doing so should be studied more carefully to achieve both better understanding of the processes and allow for possible optimization.
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