Plasma plume composition of a pulsed plasma thruster fed with perfluoropolyether

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Abstract: Plume composition of a 1 J pulsed plasma thruster (PPT) fed with non-volatile liquid propellant (perfluoropolyether – PFPE) was studied with a combination of retarding potential analyzer and time of flight approach. The plume was found to be composed mainly of fluorine ions (up to F^{6+}) – similarly to PPT operated with polytetrafluoroethylene (PTFE, Teflon) propellant. Due to the varying amount of liquid propellant and resulting measurement noise, presence of other species was not entirely clear.

I. Introduction

THE growing importance, both commercial and scientific, of CubeSat portion of the space technology domain has led to increased demand for Electric Propulsion (EP) solutions that would be suitable for these satellites with respect to power consumption, weight and size.[1] Among the advanced technologies, e.g. FEEP, electrospray, ion-gridded, and Hall thrusters, the relative simplicity of pulsed plasma thruster (PPT) seems to be an advantage in the context of CubeSat requirements, especially due to lack of neutralizer, virtually no standby power and regulated power consumption thanks to pulsed mode of operation.[2] However, the PPT tends to fall behind the other EP technologies because of its notoriously poor thruster efficiency stemming mainly from low propellant utilization.[3]

Apart from the known detrimental effect of late-time ablation in which a significant amount of propellant is expelled with low velocity after the discharge[4], experimental data of plasma velocity have hinted the presence of highly charged ions[5-6] which could also contribute to the decrease of thruster efficiency due to the large ionization cost of higher charge-states. To better understand this source of inefficiency, the exact composition of plasma in PPT must be known. However, in the most common method of optical spectroscopy, the measurements are often limited to visible range of the spectrum (where highly ionized elements do not emit light) and cannot provide quantitative information on the relative amount of species. Therefore, another diagnostic method must be considered, suitable for multi-species, non-uniform, unsteady, flowing plasma of PPT.

As an alternative to optical spectroscopy, mass spectrometry using a combination of retarding potential analyzer (RPA) and time-of-flight approach was proposed by Barral et al.[7] which allowed them to identify in PPT fueled with perfluoropolyether (PFPE) some of the higher charge-state ions like F^{4+}. The results, however, were inconclusive due to relatively low resolution and large noise. In the present work this method was revisited to study the composition of plasma emitted by a 1 J PPT fed with PFPE propellant with greater accuracy. This was achieved thanks to automated fueling system which allowed obtaining larger dataset (statistical improvement of signal-to-noise ratio) and enhanced experimental setup (increased measurement resolution). This method has been recently used to study the plume of PPT with polytetrafluoroethylene (PTFE) propellant.[8]

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II. Experiment

A. Thruster

The thruster used in this work, shown in Fig. 1, was a rectangular PPT with 2.16 μF capacitor bank typically charged to 1000 V (about 1 J of energy) and fueled with liquid propellant. The non-volatile PFPE propellant (perfluoropolyether, Fomblin Z25) was supplied in controllable doses by a dedicated fueling system into the groove of a ceramic distributor located between the main discharge electrodes. The dispensing groove was 0.8 mm wide and 10 mm long. Due to negligible evaporation losses thanks to the very low vapor pressure of PFPE (about 10^{-8} mbar), no synchronization between fueling and discharging was necessary. For nominal operating conditions (capacitor bank voltage 1000 V, firing frequency 1 Hz) one dose of fuel was enough for approximately 500 discharges. The average mass bit was approximately 4.72 μg per shot.

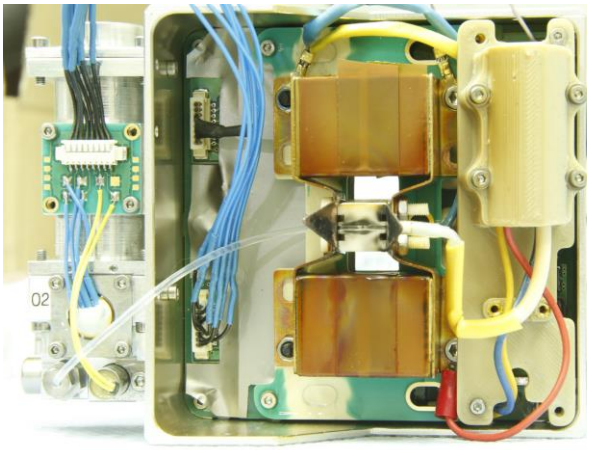

Figure 1. The pulsed plasma thruster that was used in this study. A two-part capacitor bank is visible in the center with electrodes converging around the ceramic distributor with horizontal dispensing groove. On the left-hand side there is a dedicated fueling system with integrated tank. On the right-hand side there is a transformer supplying high-voltage pulses to the spark plug igniter inserted into the common cathode.

Typical discharge current and voltage waveforms are presented in Fig. 2. Due to the low inductance design of the capacitor bank, the discharge time was short – approximately 1.6 μs. Typically about 1% of the energy was left in the capacitors after each shot, as the discharge tended to end after three half-periods of the underdamped harmonic oscillator waveform.

More detailed description of this thruster is presented in another paper – IEPC-2024-388.[9]

B. Experimental Setup

The experimental setup was exactly like in Ref. 8. The thruster was installed in a 2.5 m^3 vacuum chamber. During firing with 1 Hz frequency the pressure inside the chamber oscillated between $5x10^{-7}$ mbar and $1x10^{-6}$ mbar, so charge-exchange effects were assumed to be negligible.[10-11]

In front of the thruster two retarding potential analyzers (RPA) and one Faraday cup (FC) diagnostics were mounted, as shown in Fig. 3. The RPAs were commercial button probes from Impedans Ltd. and the FC was house-made. One RPA and the FC were attached about 30 cm from the thruster to an arm of a rotary stage with vertical axis of rotation located at the distributor surface. The FC measurements were collected with varying angular steps in range from -85° to +90° (-90° was unavailable due to space constraints) with respect to thruster axis, and the RPA measurements were carried out for five angular positions: -60°, -30°, 0°, 30°, and 60°. The second RPA was stationary and mounted in front of the thruster at a distance of 1.4 m. Collectors of all probes were biased to -20 V, and the electron repelling grids of both RPAs were biased to -40 V. The ion repelling grids were biased from 0 V to 250 V in steps of 5 V. Additionally, a simple magnetic probe was installed about 5 cm directly above the thruster to provide discharge-related signal for triggering.

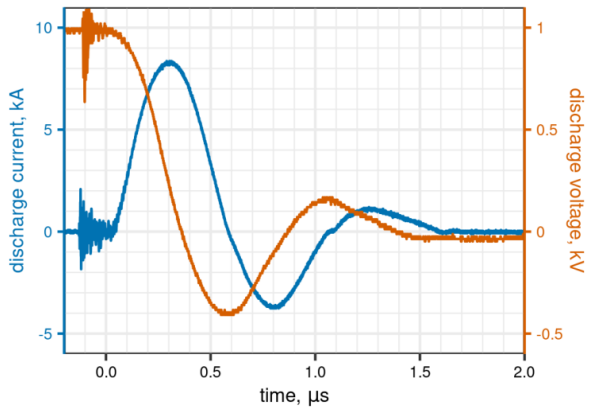

Figure 2. Typical discharge current and voltage waveforms of the studied PPT fed with PFPE propellant. The high-frequency noise at the beginning is the result of the high-voltage igniter operation.

All signals were acquired with PicoScope 4824A PC oscilloscope with 20 MHz bandwidth and 12 bit vertical resolution.

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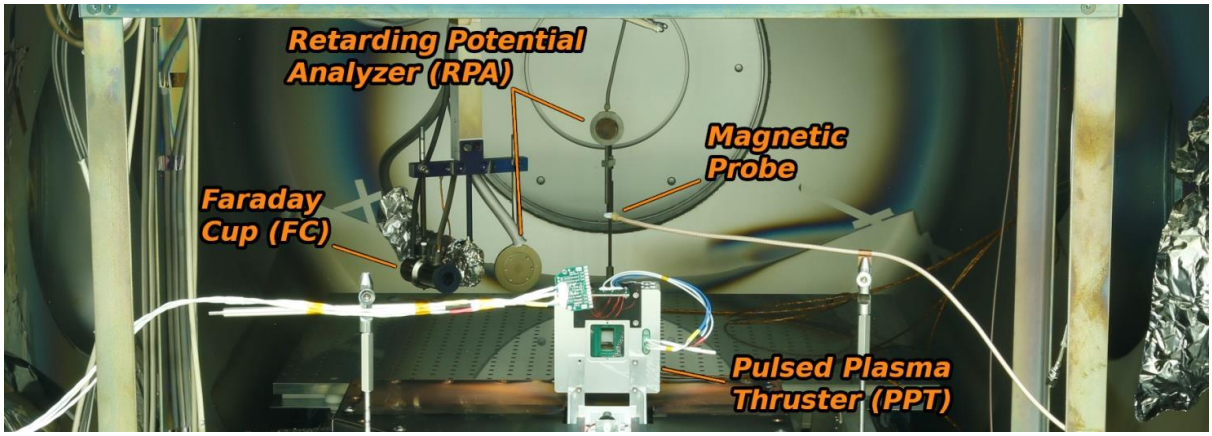

Figure 3. Experimental setup inside the vacuum chamber. One FC and one RPA were mounted on an arm rotating about the thruster. Another RPA was stationary at the other end of the chamber. A simple magnetic probe for triggering was hanging directly above the thruster. In this photo the thruster was installed with PTFE propellant block and therefore lacked the PFPE propellant tank.

III. Methodology

The methodology was similar to the one that was used earlier for such measurements with PTFE.[8] Below, only the concept of the time-of-flight measurements and the main differences with respect to the previous study are presented.

The time-of-flight approach to probe measurements is based on the energy conservation for ions,

$$q_i V = \frac{1}{2} m_i v^2, \tag{1}$$

where velocity is

$$v = \frac{L}{t - t_0}, \tag{2}$$

in which L is the distance from PPT to the probe and t_0 is some unknown time at which ions leave the thruster. Such formulation requires that ions are created and accelerated over distance much smaller than L and over time much smaller than $t - t_0$. Both requirements hold for this thruster.[8] Therefore, for all ions with energy-per-charge V arriving to the probe at time t the following is true:

$$V = \frac{1}{2} \frac{m_i}{q_i} \left(\frac{L}{t - t_0} \right)^2. \tag{3}$$

This means that every ion species drawn on (V, t) plane should lie on separate hyperbola depending on its mass-to-charge ratio m_i/q_i. Thus, by mapping the (V, t) plane, for example with a retarding potential analyzer, one can then look for distinct hyperbolic curves and identify ion species. Moreover, because the position of an ion along the hyperbola depends on its energy, it is also possible to retrieve energy distribution function for each identified species. This technique was described in our previous paper.[8]

Contrary to the study with PTFE, here the thruster could be positioned only in one way (with discharge electrodes expanding horizontally, as in Fig. 1) due to the risk of spilling the liquid propellant, so both FC and RPA measurements were carried out only in one plane. Consequently, without the knowledge of the other plane it was not possible here to obtain the total ion charge emitted from the thruster and thus individual efficiency components (beam divergence, mass utilization, energy utilization).

Additionally, the periodic refilling of the dispensing groove every 500 shots entailed some not negligible

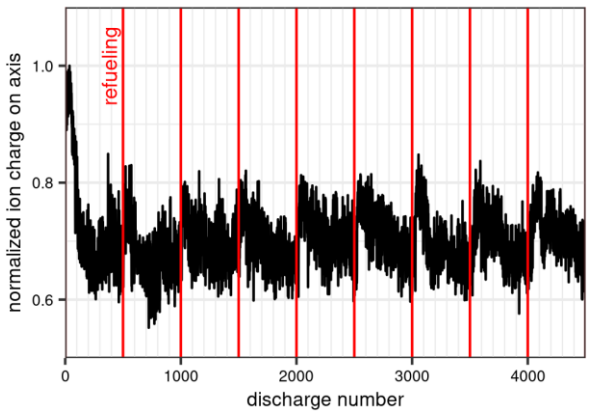

Figure 4. Periodic changes of FC measurements due to fueling cycle with PFPE.

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changes in the thruster operation during the measurement session, which was not present in the case of solid propellant. This is illustrated in Fig. 4 for FC. After each refueling event (lasting about 30 s) the larger amount of propellant available for the discharge resulted in an increase of ion signal. Because the difference seemed to be highest at the beginning of every new cycle of 500 shots, the signals from the first 100 shots of each cycle were discarded. The rest of the data was averaged over 50 signals per setpoint.

IV. Results and Discussion

A. Retarding potential analyzer

The ion charge collected by the distant, stationary RPA is shown in Fig. 5. Some "aliasing" pattern is visible in vertical direction on the left-hand side of the data, which stemmed from the periodic refilling of the distributor with propellant. Despite that, experimental data aligned into curves that clearly matched theoretical hyperbolas of the first six ionization states of fluorine – the element most abundant in PFPE (over half of atoms). Some faint traces of

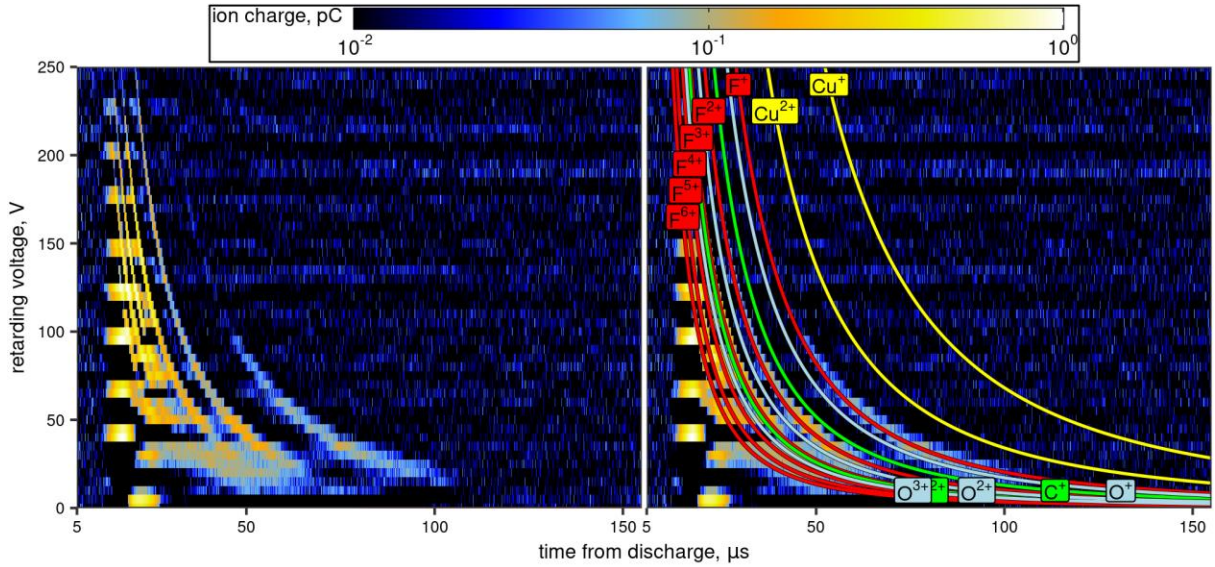

Figure 5. Voltage-time map of ion charge from PFPE measured on axis 1.4 m from the thruster with the stationary RPA. On the right-hand side panel the data were drawn together with theoretical hyperbolas.

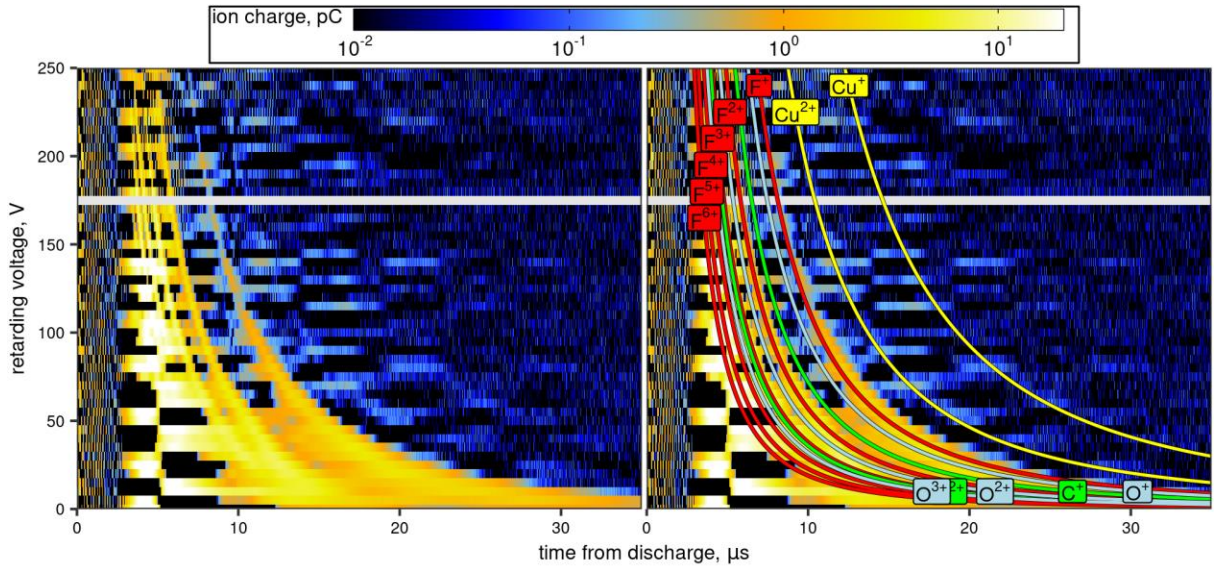

Figure 6. Voltage-time map of ion charge from PFPE measured on axis 30 cm from the thruster with the rotating RPA. On the right-hand side panel the data were drawn together with theoretical hyperbolas.

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oxygen ions O^{2+} and O^{3+} were also found in the obtained traces, although their low quantity was barely above the noise level. Carbon was not detected at all in the distant RPA data. These results were similar to traces obtained previously by Barral et al.[7] for PFPE-fed PPT of similar energy, where the plasma seemed to be dominated by fluorine ions.

Closer to the thruster, the data exhibited significantly more noise and the pattern related to refueling cycles was also more pronounced (see Fig. 6). At such small distance, however, some previously invisible traces (like O^{+} ions) started to appear, whereas other (like O^{3+}) were lost. Trace amounts of copper (Cu^{+} and Cu^{2+}) from the discharge electrodes were also detected. However, carbon ions still could not be discerned in the obtained signals.

Traces from RPA at other angles are shown in Fig. 7 for completeness, but due to worse signal-to-noise ratio they do not provide much more information.

For solid PTFE[8] the plasma also consisted mainly of fluorine ions with charge-states up to 6+, highlighting the similarity of these two types of propellant (chemical composition of PTFE and PFPE is similar, and solid-liquid phase transition energy can be neglected due to being much smaller than ionization energies). However, because of smaller noise in the case of PTFE some traces of carbon were eventually detected close to the thruster and the copper lines were also clearer than in this experiment with PFPE.

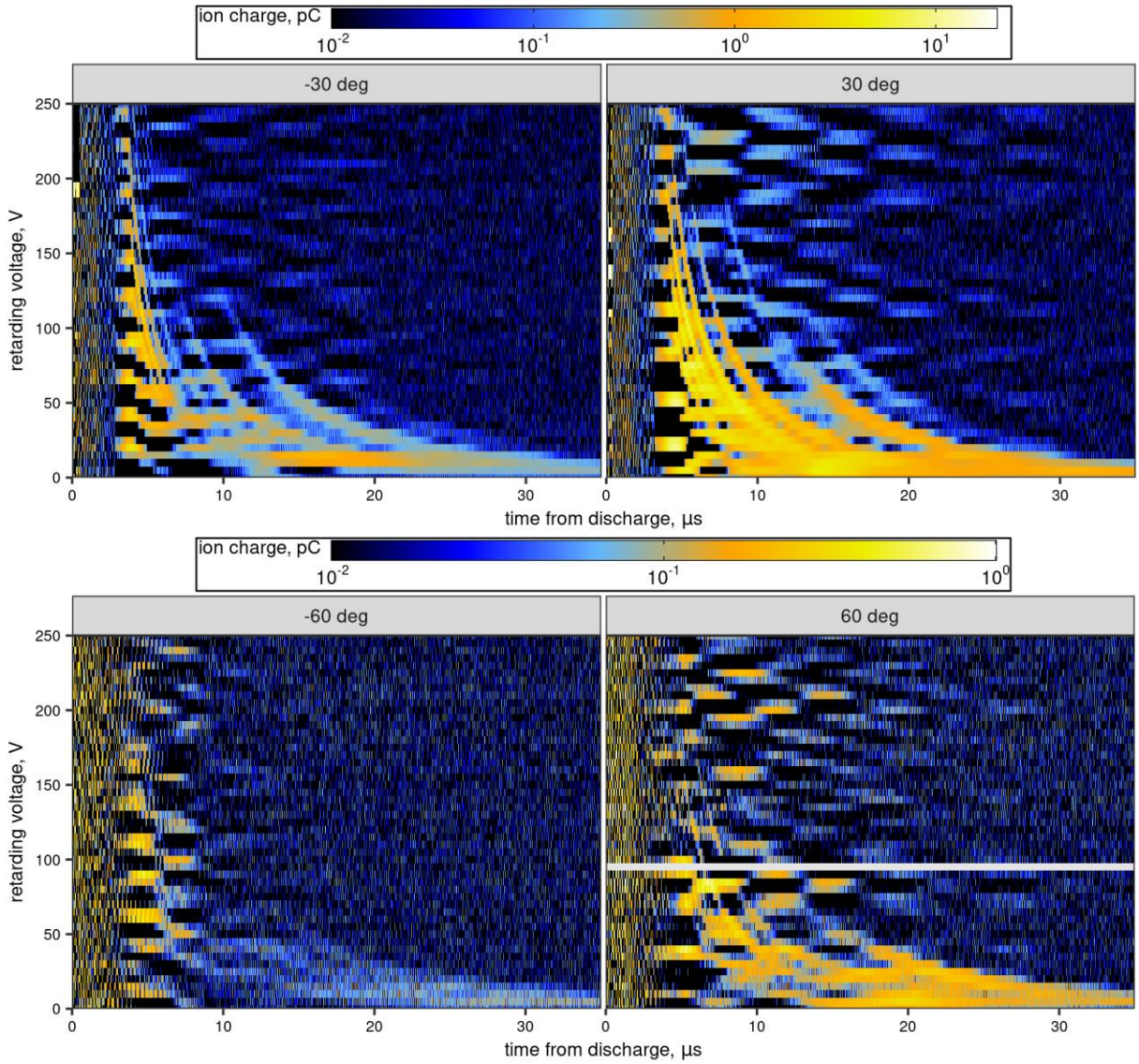

Figure 7. Voltage-time map of ion charge from PFPE as measured with angularly driven RPA at different angles. Distance from the thruster to RPA probe was 30 cm. Larger signal for positive angles stemmed from the angular offset visible in Fig. 9.

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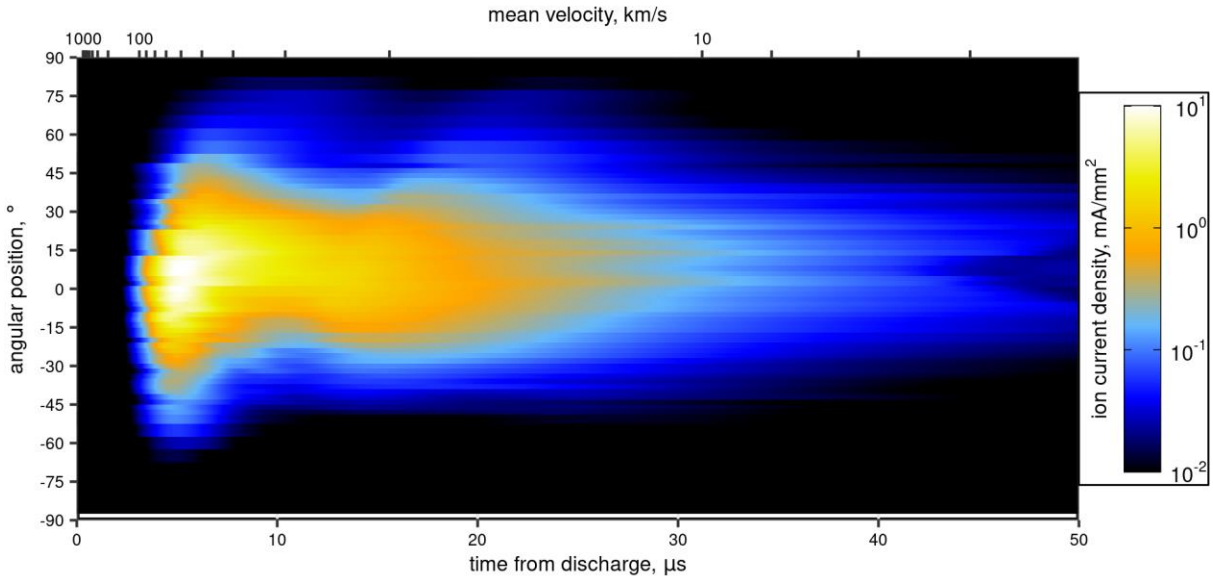

Figure 8. Time evolution of ion current density measured in one plane by Faraday cup for PFPE.

The next step would be to go along these hyperbolas and count the number of ions versus time or voltage, as was done for PTFE.[8] In this way it should be possible to retrieve velocity and energy per charge distributions of individual fluorine species. Nevertheless, it can already be seen that for PFPE the relative magnitude of the signals is shifted towards the higher charge-states (e.g. compare F^+ trace here and in Ref. 8).

B. Faraday cup

The ion signals obtained by angular displacement of Faraday cup are shown in Fig. 8. Here again a pattern related to refueling cycle is visible. Apparently, different amount of propellant in the dispensing groove influenced the fastest ions. When the amount of propellant was lower, the velocity of the fastest ions grew to well over 100 km/s. The mean velocity of fastest ions was larger than in the case of PTFE.[8] The beam was also visibly dominated by the high-energy ions at larger angles.

Integrating ion current density at each angle, an angular profile of the beam was obtained (Fig. 9). The profile in this specific plane exhibited similar features to the analogous profile of the thruster firing with PTFE. In particular, the shape was Gaussian-like in the center, but at larger angles the charge density was significantly larger, especially when considering that these angular positions were in the shadow of discharge electrodes. Such increase was not related to the charge-exchange effects, but rather to the plasma expansion from other regions of the beam.[8] Offset from the axis (about 7° towards the cathode side) was larger than in the case of PTFE (1°) – the reason for this is for now unknown.

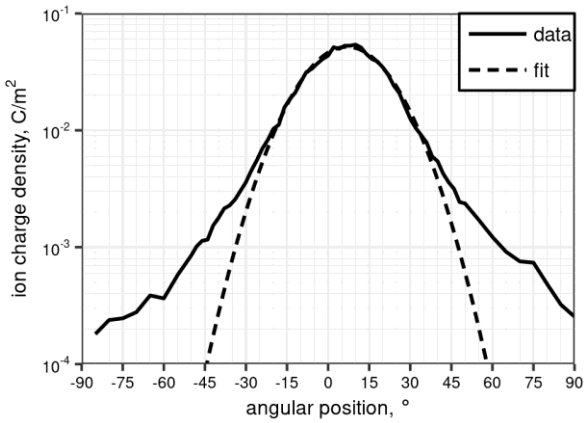

Figure 9. Angular profile of the ion beam in one plane for PFPE. A Gaussian was fitted for reference. Positive angles were on the cathode side of the thruster.

V. Conclusions

The measurements presented in this work for 1 J pulsed plasma thruster fed with liquid PFPE propellant showed similar beam composition to PTFE. In both cases the beam was dominated by highly ionized fluorine (up to F^{6+}), whereas the rest of the atoms (oxygen and carbon in case of PFPE, carbon in case of PTFE) was almost absent. This work provides further evidence against the assumptions of local thermal equilibrium and the presence of only the first ions in propellant-like proportions that are usually made in numerical and analytical models of PPT discharge.

The contribution of high charge-state ions in the beam seems to be larger in PFPE, but further analysis is

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needed. This may be the result of different surface area of the propellant for the same discharge energy.

To further improve data resolution, in subsequent experiments the voltage step of RPA should be reduced, whereas to lower the noise, the averaging of the data should be done in the same phases of fueling cycle. However, both will significantly extend the duration of the measurements.

Acknowledgments

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