A Neutralizer-Free Gridded Ion Thruster Embedded Into A 1U Cubesat Module

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Dmytro Rafalskyi[1]
SATT Paris-Saclay, Orsay, 91400, France
ThrustMe, Paris, 75014, France
LPP (CNRS, Ecole polytechnique), 91128, Palaiseau, France

and

Ane Aanesland[2]
ThrustMe, Paris, 75014, France

Abstract: ThrustMe, in partnership with the Laboratory of Plasma Physics and SATT Paris-Saclay is developing a complete propulsion system based on a patented ion thruster technology, called "Neptune". A miniaturized version with the thruster, power processing unit and solid propellant is fully imbedded into a one-unit Cubesat module (a 10 cm cube of 1 kg). The thruster has strong technology heritage from classical ion thrusters, but with significant innovation in the acceleration mechanisms using RF voltages applied to a set of grids, instead of the conventional DC voltage. This RF acceleration leads to a continuous ion beam neutralized by electrons exiting the thruster in short instants during the RF cycle. In this way, there is no need for an additional electron neutralizer, and thus the system is ideal for miniaturization as well as cost effective mass production. Solid iodine is integrated into the thruster body to simplify the propellant storage and flow control. The PPU based solely on radio-frequency modules operating in the MHz frequency range is also developed and can operate with powers from 20 to 60 W. This RF power is used for plasma generation, ion acceleration, neutralization and iodine flow control allowing the power system to be fully integrated into the 1U Cubesat module. The complete system is tested in various vacuum facilities where time-averaged and time-resolved electrostatic measurements of beam currents/fluxes and ion energies are compared with direct thrust measurements.

Nomenclature

RF	=	radio frequency
ω, ω_{pi}	=	RF voltage angular frequency, ion plasma frequency
IEDF (EEDF)	=	ion (electron) energy distribution function
$f(\Theta)$	=	ion angular distribution function
COG	=	centre of gravity
PIC	=	Particle-in-cell

[1] Maturation engineer at SATT Paris-Saclay, CTO and founder of ThrustMe, hosted at LPP, dmytro.rafalskyi@thrustme.fr.
[2] CEO and founder of ThrustMe, ane.aanesland@thrustme.fr.

I. Introduction

Recently, a new *quasi-simultaneous* ion propulsion concept has been proposed [1,2], originally called "Neptune" due to the acronym of the first research project funding this development[3]. Here ions and electrons are co-extracted from plasma and accelerated to high velocities, due to capacitive divider and self-bias effects[4,5] achieved within the double-grid extraction system (see Fig. 1). Briefly, when RF voltage is applied only between two closely spaced grids being in contact with plasma, the equivalent circuit is similar to the circuit of the asymmetric capacitive discharge[5,6]. The electrical asymmetry required for the capacitive divider effect follows from partial screening of the second grid from plasma by a first one [2].

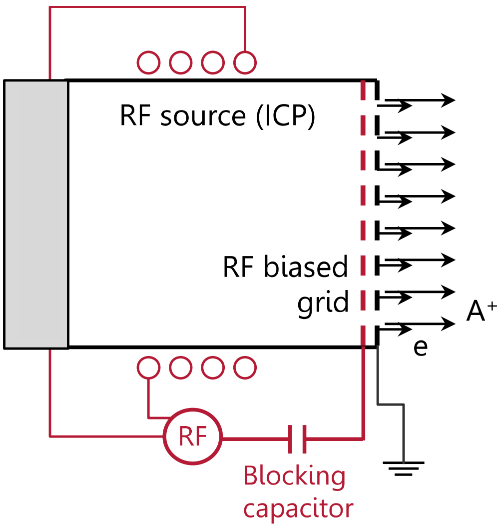

Figure 1. The RF acceleration based thruster.

One difference of RF acceleration thruster from a classical gridded thruster (as "RIT" for example [7]) is that the gridded extraction system is powered with RF voltage instead of DC as seen from Figure 1. The different response time of ions and electrons to the oscillating field leads to positive rectification of the sheath voltage (so called self-bias effect) [4,5]. Thus, massive ions are accelerated in front of the apertures of the second grid by an averagely positive potential difference and leave the thruster at high velocities, generating thrust. At the same time, much lighter electrons responding to almost simultaneous electrical field are extracted from plasma in a short bursts when oscillating plasma potential approaches zero values. Finally, the presence of a blocking DC capacitor in the system ensures absence of any DC current, thus the total amount of extracted ions and electrons is time-averagely equal. This produces a well-compensated beam composed of continuously accelerated ions and pulsed electrons [2,8].

This acceleration concept was proposed in 2014 and proof-of-concept has been achieved for Xe, Ar and N_2 gases, where it was found that the RF ion acceleration has the same efficiency as traditional DC acceleration [2]. The floating potential of the beam is found to be lower than in the case of DC acceleration with neutralizer, which can be explained by highly directional extraction of electrons with the RF acceleration scheme.

One of the important questions to this concept consisted in possible downscaling limits, since there is a significant and still growing interest for propulsion systems adapted for small spacecrafts, where the electric propulsion system is usually replaced by less efficient chemical or cold gas propulsion due to problems of downscaling. In fact, the RF acceleration principle allows to reduce mass and volume of the propulsion system without reducing the performance due to the absence of a separate neutralization system that includes additional power supply, gas feed line and neutralizer itself. The possibility to achieve the self-bias effect in the miniaturized gridded thruster has been recently demonstrated with a so called "Miniature" system[9], currently operating with Xenon and Iodine propellants and having 2 cm diameter. This system is under intensive development towards a complete propulsion system product, and is planned for in-orbit-demonstration in late 2018. Flight version of the thruster will be embedded into a 1U "plug-and-play" propulsion module that require only the dc voltage input from the satellite bus for the operation. This article presents the current development stage and first test results of this propulsion module.

II. Development progress

High level target specs of the propulsion module are represented in Table 1 below.

Table 1. High level target specs for the propulsion module

Parameter	Expected value (approximate)
Total power consumption	30-60W
Propellant	Xe, I2
Thrust	0.2-0.7 mN
Specific impulse	>1000 at max power
Number of ignition cycles	>100

Wet mass (integrated fuel version)	<1.3 kg
Size of the propulsion module	1U (10x10x10cm)
External electrical inputs for the module operation	12V DC power input, CAN or I2C interface for communication
Interface with a S/C thermal management system	Not required, excessive heat radiation is managed within the propulsion module
Propellant storage and flow control	Internal (I2 version) or internal regulator with external tank (Xe version)

The development progress of the thruster and integrated propulsion system is presented separately in subsections II A and II B below, while the subsection II C briefly describe progress achieved during the first part of a test campaign at ONERA the French Aerospace Lab.

A. Thruster

A developed thruster is schematically shown on Fig. 2. It produces a 20mm diameter beam and the cylindrical discharge chamber has aspect ratio of ~1. Propellant (Xe or iodine) is fed through a distributed gas injection system and ionized using the RF antenna placed around the discharge chamber. The ion/electron optics set consists of two molybdenum grids and is powered with RF voltage. The external Faraday cage suppress EMI resulting from both the RF antenna and RF-powered grids.

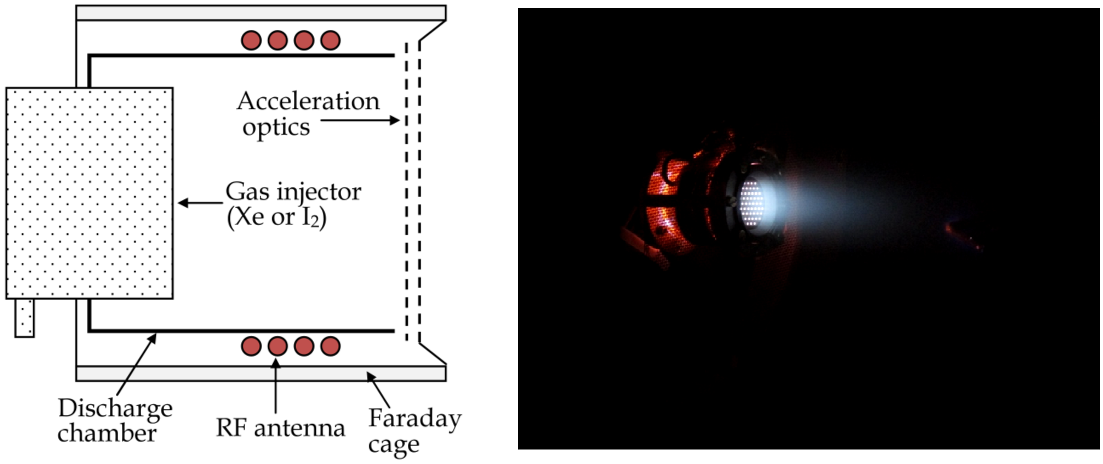

Figure 2. Schematic representation of a thruster and non-integrated thruster firing on Xe.

The expected thruster performance range is shown in Table 1 and was firstly based on results of theoretical modeling, including 0d low pressure global model (similar to work[10]), transformer model [10] and 2D PIC simulation of RF particle acceleration, and afterwards corrected with results of experimental measurements of plasma parameters inside a non-integrated thruster and beam measurements in a relatively large (0.7m length) low pressure vacuum chamber. A picture of the non-integrated thruster prototype running on Xe in the test chamber is shown on Fig. 2. Experiments conducted with a non-integrated thruster have been focused on three important aspects: i) general operational tests including thermal cycling, outgassing, reliability and shielding tests; ii) validation of theoretical plasma and beam acceleration models; iii) development of reliable algorithm for repetitive plasma ignition. These experiments started on July 2016 and successfully terminated early 2017. Several modifications to the thruster design have been implemented. The majority of these modifications/improvements solved traditional propulsion system engineering problems, however some challenges are new to the propulsion community since the RF acceleration is a very recent concept (first publication in 2014[2]) and we will therefore emphasize on these issues below.

The most important difference of the developed thruster from classical ion thrusters consists in the RF method for ion acceleration with the following electron co-extraction. Though various advantages, the RF nature of the particle acceleration requires development of new, more sophisticated theoretical models for ion acceleration, as well as new diagnostics approaches for the ion beam measurements. To model the ion and electron trajectories between the grids and in the near field plume region we use a 2D particle-in-cell (PIC) code in a planar geometry.

The code is still under development and will be published later, while here we present only a few important results corresponding to an interesting limit case when the ion transit time through the grids spacing is comparable to RF period (therefore the worst case scenario). This may happen either due to too high ion current density or too low frequency for the given set of grids.

In this case the ion energy spread is very significant, so ion focusing become an important problem. This is demonstrated on Fig. 3 showing the IEDF for the case when ion plasma frequency approaches the acceleration frequency (the RF voltage amplitude is 1500V). The IEDF has two major peaks, around 900 eV and 2400 eV and is centered around 1500 eV which corresponds to the averaged value of a potential difference between the grids. Therefore, successful ion extraction requires focusing of both the low- and high- energy peaks, which impose certain limits on the range of ion current density and geometry. The low acceleration frequency is also leading to significant pulsations on the ion beam current measured at the exit of acceleration system (see Fig. 3), though they found to be negligible at few cm from the exit. It should be noted here, that even in this case, the average values of the extracted ion and electron fluxes are equal to each other, and therefore the beam is quasi-neutral. The angular distribution of ions in the beam generated at these conditions can still result in high angular efficiency (see Fig.4).

Therefore, development and optimization of the extraction optics for the cathode-less ion thruster with RF

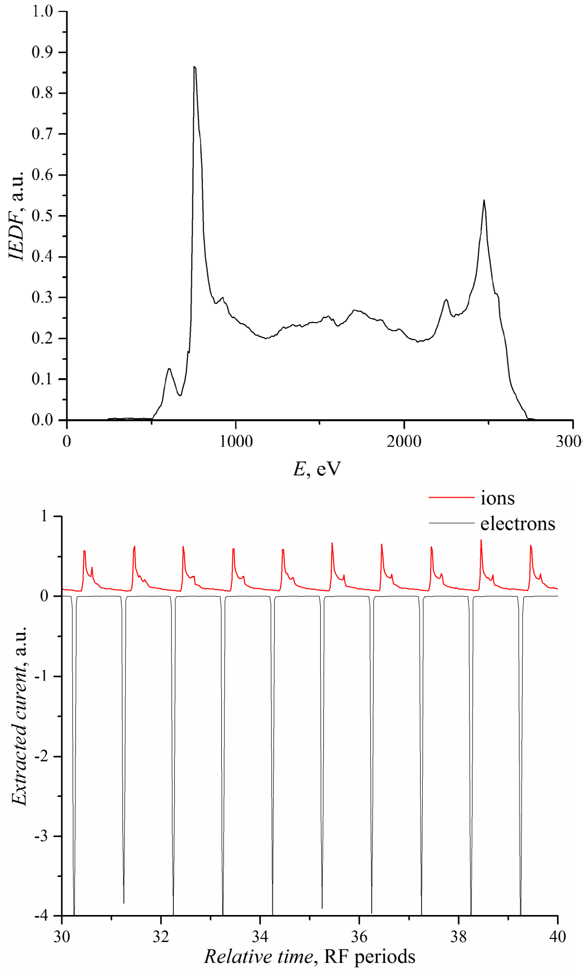

Figure 3. PIC simulation results. *IEDF and time variation of extracted currents obtained for the worst case scenario when $\omega \sim \omega_{pi}$.*

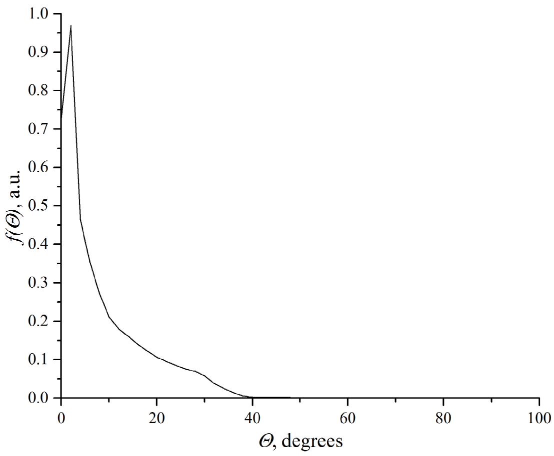

Figure 4. PIC simulation results: continued. *Angular distribution function of ions for the worst case scenario when $\omega \sim \omega_{pi}$.*

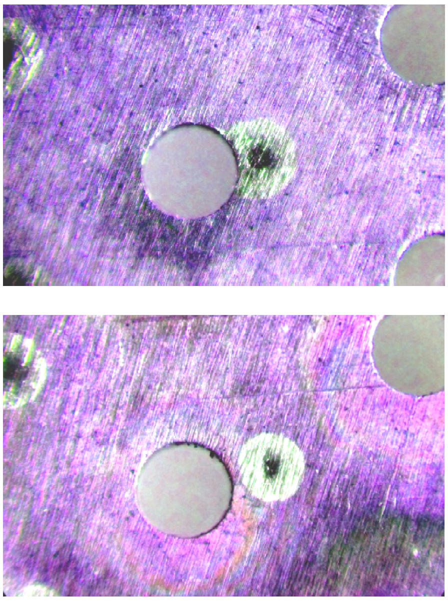

Figure 5. Footprints of beamlets. *Obtained on miss-aligned acceleration grid, on the grid centre (top) and periphery (bottom). Purple color corresponds to the initial surface condition, light green indicate areas with intense sputtering.*

acceleration is a complicated task requiring complex consideration of various operational parameters, especially if wide range of throttling is required. Due to our challenging development schedule, we solved this problem via several semi-empiric iterations, where each iteration step included simplified modeling with following short-time experimental tests. Experimental measurements consisted of ion current measurements as a function of RF voltage around a perveance limit, IEDF and EEDF measurements, and control of the beamlet footprints. Ion current and energy distribution functions were measured using standard electrostatic diagnostics as planar (Faraday) probes and RFEA (RPA). It should be mentioned that with RF acceleration the ion beam current cannot be reliably measured using classical methods used in the ion thruster community where differential grid current is suggested to be equal to the beam current. This is because firstly, both ions and electrons are extracted so the average current is close to zero; and secondly, the value of the ion current is negligible comparing to the RF displacement current.

Fig. 5 shows the footprints of ion beamlets at the downstream grid, obtained by artificial miss-alignment of the two grids (2 minutes run on Xe at 45 Watts of total RF power). It is clearly seen that ions are well focused, i.e. the beamlet size at the acceleration aperture entrance is smaller than the corresponding size of the aperture. In this case the operation regime was set using results from modeling. Further investigation (both theoretical and experimental) is naturally needed in order to understand erosion effects at a long timescale and at different conditions.

B. Propulsion module

As already mentioned, the propulsion module has 1U cubesat form-factor geometry, maximal weight of 1.3 kg and contain all necessary electronics for the thruster operation. The propulsion module presented here was specially developed for the first on-ground tests and is simplified comparing to the flight version. In this case the fluidics and general microcontroller were not embedded in the module but fed from an external source. The integrated PPU, illustrated by a block diagram on figure 6, consisted of two RF generators powered with 12V DC, two matching networks, ignition system interface and high voltage measurement system (returns RF and DC values of the grid voltage).

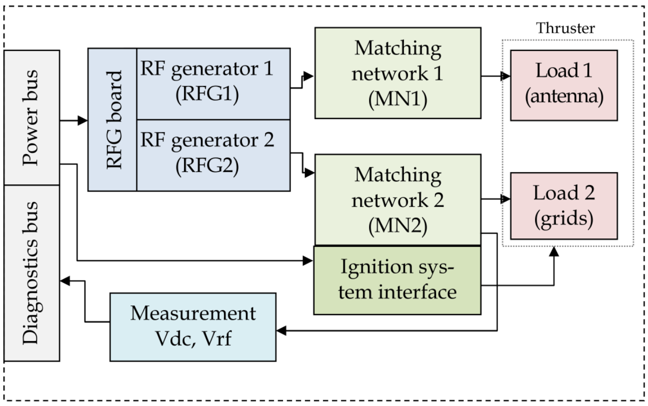

Fig. 7 shows a simplified composition of the 1U propulsion module. As seen, the thruster has a two-axis gimbal and its rotation axis is close to the exit plane. The 1U frame has a mechanical holder (on top of Figure 7) serving for mechanical connection to the pendulum during the direct thrust measurements. The center of gravity of the module is located within the 1 cm radius of the geometrical center. All electronics is COTS-based, fully developed in-house.

The propulsion module was assembled and initially tested in a cylindrical vacuum tank having 65 cm diameter and 70 cm length (see Fig. 8). Residual pressure in the chamber is better than 6×10^{-7} mBar, and pressure when thruster is firing on Xe at full power is around $(2\text{-}2.5)\times10^{-5}$ mBar. Note here, that this first test version of a propulsion module was designed to be tested with a Xe propellant only. Future versions will work on iodine propellant as well, for which we have proof-of-concept experiments.

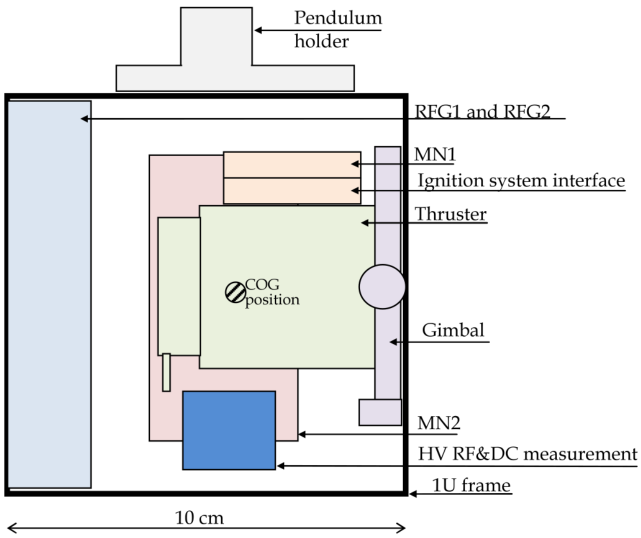

Figure 7. Schematic representation of the integrated propulsion module.

As already mentioned, this module is a simplified version of a flight-ready system. In addition to missing fluidics and microcontroller, the module thermal management is not fully autonomous and require external heat sink or cycled operation to avoid overheat of sensitive elements. We used the latter method where the standard cycle length during the firing tests was varying between 1 and 10 minutes with following 15 minutes of cooling down. Mechanical connection of the module to the vacuum chamber was performed using two relatively thin (4 mm diameter) metal rods of 60 mm length each, in order to suppress heat exchange between the module and tank. The temperature distribution in the module was controlled by thermal imaging, using the IR transparent germanium window and markers of defined emissivity attached to different elements in the module.

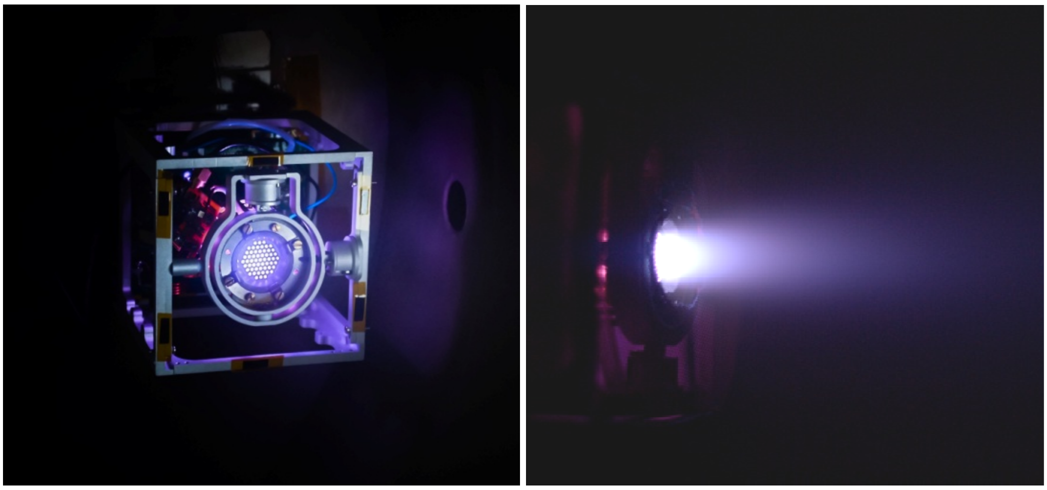

Figure 8. Assembled propulsion module during operation tests.

C. Test campaign

After various in-house tests, the propulsion module was transported to the ONERA (French Aerospace Lab) to carry out a direct thrust measurements campaign (see Fig. 9). The campaign is divided onto two major parts, with the target parameters listed in a Table 2 below. The first part has been completed in March-April 2017 and the second part is planned for Q4 of 2017.

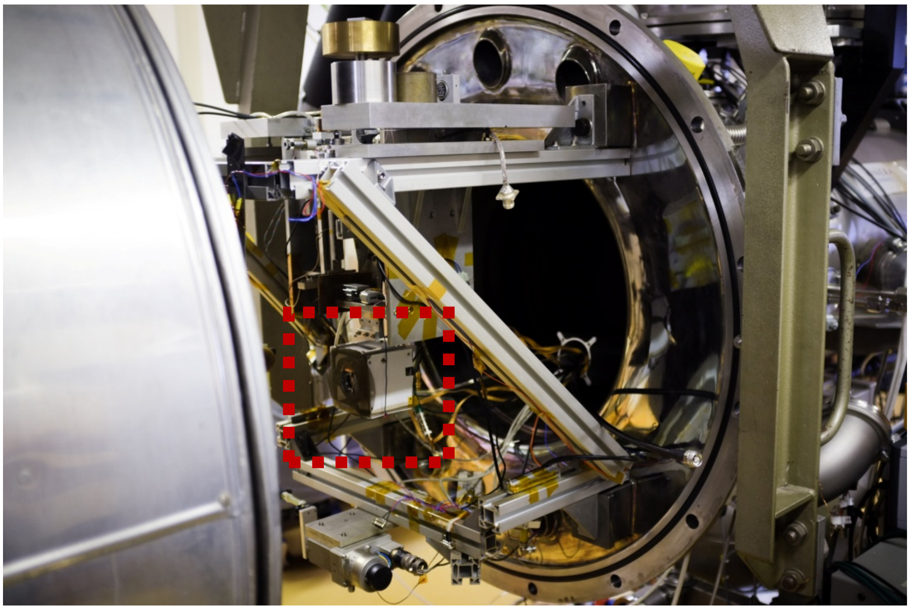

Figure 9. Propulsion module on a thrust balance at ONERA. *The red square shows 1U module installed on a free pendulum for direct thrust measurements.*

Table 2. Test plan of a first campaign

Parameter	Test campaign – part 1	Test campaign – part 2
Total power consumption	>30W	30-60W
Propellant	Xe	Xe, optionally I2
Thrust	0.1-0.3 mN	0.3-0.7 mN
Number of ignition cycles	>10	>20
Dry mass of the propulsion module	<1 kg	
Size of the propulsion module	1U (10x10x10cm) + holder	
External electrical I/O for the module operation	12V DC power input, external ignition power supply, analog diagnostics outputs, no intelligence	12V DC power input, I2C interface for communication
Interface with a thermal management system	N/A	
Propellant storage and flow control	Completely external	Internal (I2 version) or internal regulator with external tank (Xe version)

As follows from the table, the first part of the test campaign is focused on general tests of the simplified module, described in the section II B. The fluidics is represented by standard industrial mass flow controller connected to mechanical valve, pressure transducer and regular 30 Bar Xe bottle (all mounted outside the vacuum tank); ignition and operation control is performed from outside. The 5 m long tank is pumped using primary, turbomolecular and cryogenic pumps, allowing to reach the residual pressure of the order of 10^{-7} mBar.

During the first part of campaign, in total 34 operation cycles have been performed. Each cycle consisted from plasma ignition, a pre-heating (with only plasma switched on) and acceleration phase, when the thrust was measured. Example of raw data output from a thrust balance is shown on Fig. 10, demonstrating on-off steps. Complete set of properly processed data will be issued only after the second part of the test campaign is finished.

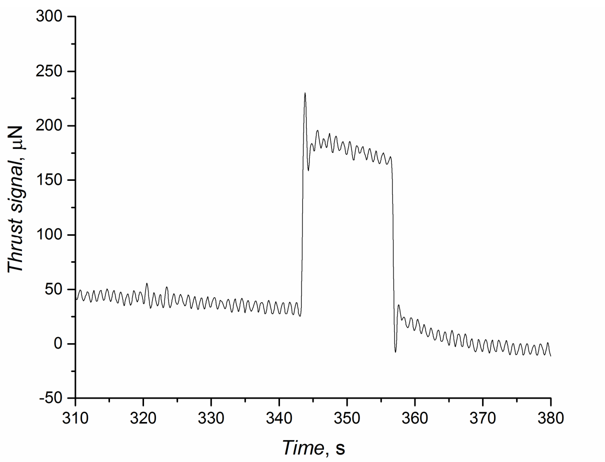

Figure 10. Thrust signal during a short on-off cycle. *The data represented here is a raw data and contain uncompensated offset drift and unfiltered oscillations; the thrust signal is relative, not absolute value.*

III. Conclusion

A propulsion module based on a new *quasi-simultaneous* ion propulsion concept has been developed and tested. The module follows the 1U Cubesat standards, and contains thruster and a PPU; future version will also be equipped with fluidics and FCU. Two versions of the module are under development using Xe and I2, and the latter will have an internal propellant tank for simplified fluidics system. The Xe version of the propulsion module has been tested in a medium vacuum chamber available at LPP and also in a large chamber at ONERA. The test campaign is not yet finished, however the preliminary results agrees well with the theoretical predictions.

Acknowledgments

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