# Development and In-Flight Testing of an Iodine Ion Thruster

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## ABSTRACT

The increase in the number of small satellite missions is enabling the development of new mission scenarios, requiring in turn further miniaturization of the systems onboard. An example is the deployment of small satellite constellations, which typically require onboard propulsion to perform phasing, collision avoidance and deorbit maneuvers. In this work we describe the development, testing and first in-space demonstration of a one Cubesat unit standalone iodine-fueled electric propulsion system based on a gridded ion thruster. The propulsion system, called NPT30-I2-1U, has all the subsystems necessary to its operation integrated inside the 1U volume, such as power processing unit, operation controller and iodine propellant storage and management. An inductively coupled RF plasma source is used for propellant ionization and a two-grid assembly for ion acceleration, while the beam neutralization is achieved with a cathode-neutralizer based on thermionic hot filament cathode. The propellant is solid iodine, stored in the internal unpressurized tank and sublimated during the operation. The system can provide up to 5500 Ns of total impulse at a specific impulse up to 2450 s and thrust levels of up to 1.1 mN in the range of input power of 35-65 W. Extreme miniaturization of the system is achieved through several innovations, including pipe-less propellant delivery, custom RF generation technology, a dedicated plasma ignition system and integrated thermal management. The necessary level of robustness and safety is achieved through implementation of reliability engineering approaches: system has built-in self-test and self-tuning algorithms and several layers of security loops. It should be mentioned, that the NPT30-I2-1U is the first iodine-fueled electric propulsion system launched to space and therefore many iodine-related aspects such as a propellant storage configuration, corrosion and sublimation control, iodine plume neutralization etc., have been tested in space for a first time.

## INTRODUCTION

The main advantages of the electric propulsion over other propulsion types consists in very high exhaust speeds, and consequently specific impulses which can be achieved (in the order of 2000-4000 s). This property of the electric propulsion is even more critical for the smallest satellites (<50 kg), which typically have lack of mass budget, thus reduction of the propellant mass is of high interest. Electric propulsion requires using high atomic mass propellants for reaching sufficient thrust to power ratios[1].

Typical propellant choice for electric propulsion is xenon, as a heavy noble gas being also inert in most of conditions. The main drawback of xenon is linked to its storage complexity which require high pressure tanks to be used. Starting from early 2000s several research works proposed using iodine as a replacement for xenon due to its solid state at normal conditions and similar atomic mass to xenon[2, 3, 4,5]. Being able to combine advantage of reduced propellant mass and decrease in the system volume by using an iodine-based electric propulsion can enable the use of propulsion on many types of satellites.

This was a major motivation for developing the NPT30-I2-1U propulsion system, which combines the iodine-propelled gridded ion thruster, the power processing unit, flight controller, the thermal management system and the propellant storage inside a very little volume of less than 10x10x10 cm. To the authors knowledge, for the moment this is the smallest flight-proven standalone propulsion system based on an ion thruster. Figure 1 below shows the propulsion system.


**Figure 1: View of the NPT30-I2 1U propulsion system**

Development of the flight-ready system has been restricted in time to less than 1 year, and therefore had to follow the "new space" paradigm with agile development approach, in contrast to classical space industry development path having a typical project duration one order of magnitude larger [5].

## SYSTEM ARCHITECTURE

The main element of the propulsion system NPT30-I2-1U is the gridded ion thruster[1], which is schematically shown on Figure 2 below.

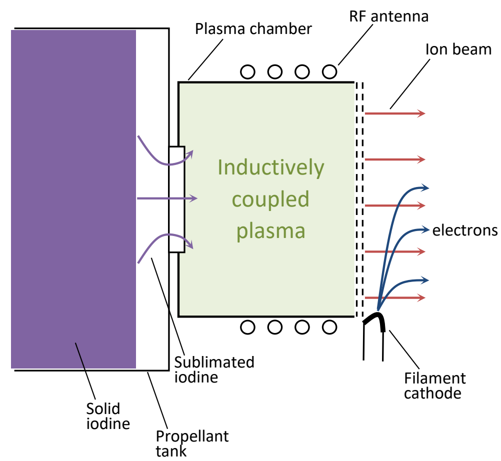


**Figure 2: Simplified scheme of the propulsion system**

The propellant in gaseous form is supplied to a ceramic cylindrical plasma chamber through the distributed gas injection system. Propellant delivery is designed as a pipe-less system, since the connection between the propellant tank and the thruster is performed only through a large surface area connection insert[6], which assures steady operation minimizing the line clogging risks[7], helping also to recuperate part of the thruster's waste heat. Iodine flow is regulated through the direct sublimation control algorithm with precise adjustments of the propellant tank temperature, which is described in detail in another work[6]. Propellant fracturing, sloshing and loss of thermal contact at zero gravity is prevented by using a porous matrix filling the tank volume. Propellant ionization is ensured by an inductively coupled RF plasma discharge[6], which has a strong advantage over other types of discharges for operation with corrosive gases due to its electrodeless excitation. The plasma chamber is terminated by a set of two metal multi-aperture grids, serving for ion acceleration. The beam neutralization is performed by a filament-based thermionic cathode similarly to the first ion thrusters tested in space (starting from SERT-1 mission by NASA[9]), but in contrast to those its mounted on the external plane close to the ion beam edge and have dedicated plume shielding. The discharge chamber has been designed with the help of analytical modeling based on a collisionless global plasma model[10,11] coupled with the transformer model of the inductively coupled plasmas; skin-effect and stochastic heating contributions have been accounted for as well[8]. The ion optics, represented by a 2-grid assembly has been developed using Particle-in-cell (PIC) simulations (using the open-source code XOOPIC1) to find a compromise solution within the target performance range.

The NPT30-I2 is largely based on the earlier NPT30-Xe operating on conventional xenon propellant[12]. Plasma generation, ion acceleration and beam neutralization systems are nearly identical, except for the development corresponding to the material selection process for the compatibility with the halogen propellant.

### *System Performance*

Target specifications for the NPT30-I2-1U prior to development are shown in Table 1 below in comparison with the final flight-ready system parameters.

**Table 1: NPT30-I2-1U system specifications**

| NPT30-I2-1U specifications | Target | Final |
|---|---|---|
| Dimensions | 1U compatible | 96 mm x 96 mm x 106 mm |
| Form Factor | 1U | 1U |
| Dry mass | < 1 kg | 950 g ± 50 g |
| Wet mass | <1.3 kg | 1170 g ± 50 g |
| Voltage input | 12-16 V, unregulated | 12-28V, unregulated |
| Communication bus | CAN, I2C | CAN, I2C |
| Thrust range | 0.5-0.9 mN or superior | 0.4 – 1.1 mN |
| Total impulse | > 3000 Ns | up to 5500 Ns |
| Total input power | < 70 W | approx. 30-65 W |
| Start-up time | < 30 min | 8-15 min |
| Radiation | LEO compatible | Al shielding 1.6mm, rad tolerant main controller and communication transceiver |
| Redundancy | Cathode neutralizer | Satellite CAN communication, tank thermal management, main power lines (including RF power and ignition), cathode neutralizer. |
| Operation control loop | Internal | Fully internal control loop, no action is required from the satellite on all stages |
| Reliability | Built-in self-test and autotuning | Built-in self-test, automated ground test sequence, autotuning |

The resulting system architecture represents an intricately interlinked arrangement, schematically shown in Figure 3 below. The figure shows the main internal heat fluxes, propellant flow, and various electrical and communication lines. Several redundant elements are present, including the neutralizing cathodes, RF power lines, external CAN communication and tank thermal management unit.

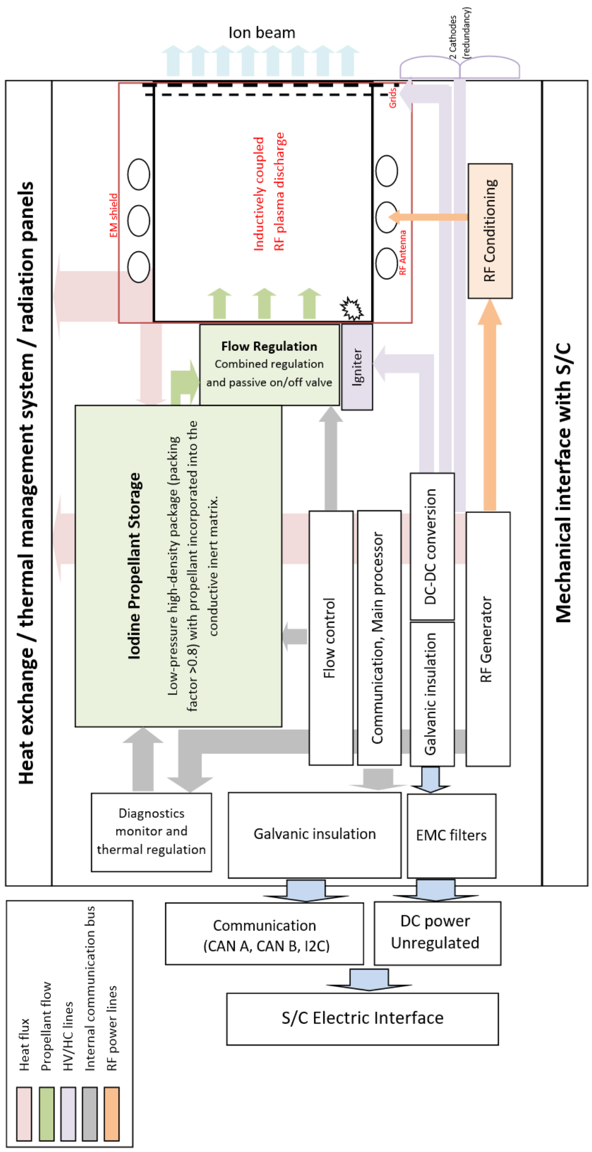


**Figure 3: System architecture**

### *Miniaturization and Propellant Specific Constrains*

The miniaturization of the system required implementation of a highly independent local thermal management design. Keeping in mind the total size of the unit (<1U) and the relatively high-power density (up to 65 W/Unit), a passive thermal management approach has been implemented, with several thermally decoupled radiation panels operated at a relatively high temperature for efficient heat irradiation. In total, 4 radiation panels are used, serving multiple functions as both structural elements, and radiation shields: a front radiator, on which the thruster head is mounted, and 3 side radiators linked to the highly loaded power processing subsystems. In addition, part of the waste heat of the thruster is redirected towards the propellant tank, resulting in a significant decrease of the required heating power in steady state operation (only around 1 Watt of electric power is drained from the power bus).

The main differences to the typical xenon-fueled thruster design[1] are linked to the corrosive nature of iodine. Previous research[13] helped to develop design guidelines for protecting the internal thruster components from halogen corrosion effects, including the plasma chamber, grid assembly, internal plasma ignition system, and the interface with the propellant delivery system. The resulting set of materials in direct contact with iodine was reduced to inert ceramics for dielectric parts and molybdenum-based alloys for conductors.

### *System Lifetime*

The main life-limiting components of the ion thruster are the grids and neutralizer cathode[1]. Downstream plume ions which strike the grids can cause sputter erosion that leads to eventual failure over time. Due to tight development and delivery schedules, complete lifetime testing to failure has not yet been performed. Lifetime assessment is instead based on theoretical modelling and erosion measurements after shorter testing times. A total accumulated testing time of 271 hours has been performed with xenon, and 120 hours with iodine (composed of 109 separate ignitions).

Erosion patterns on the acceleration grid (downstream surface) have been studied and found to be similar to classical "pits and grooves" patterns[1] (see Figure 4). Depth profiles of the erosion have been measured with a high-precision Ayonis LEOS 300 metrology machine, resulting in a prediction of over 7000 hours of operation for xenon and over 3000 hours for iodine, using a conventional 80% thickness failure criterion. This complies with approximately 2500 hours of target lifetime of the system (limited by the propellant amount).

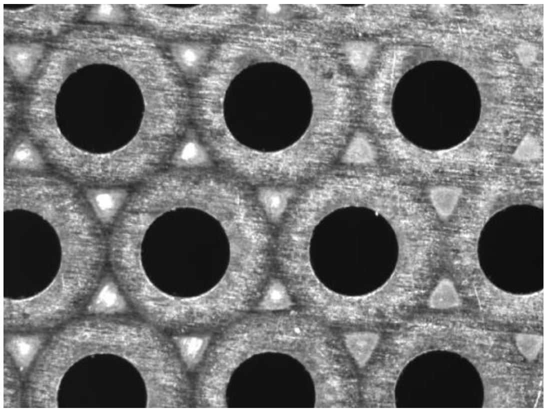

**Figure 4: Microscope image of the downstream accel grid surface at periphery, after 120 hours of operation with iodine**

The lifetime of the neutralizer cathode is limited by two main factors: (1) vaporization of the thermionic filament, and (2) erosion from iodine ion bombardment and reactive ion etching. During operation, the temperature of the cathode filament determines the emitted electron current. The vaporization rate of the filament, however, is also a function of the temperature. Figure 5 shows measurements of the emission current, as well as the predicted lifetime of the filament (assuming a conservative failure criterion equal to a 10% filament mass loss), and radiation power loss as a function of the cathode temperature. The green region shows the NPT30 operating range. As can be seen, the minimum expected lifetime due to vaporization is higher than 7000 hours. Predicted vaporization rates have been confirmed experimentally with cathodes operating for 250 hours in vacuum. The filament radius was measured, and the results are shown in Figure 6, where good agreement with theory is found.

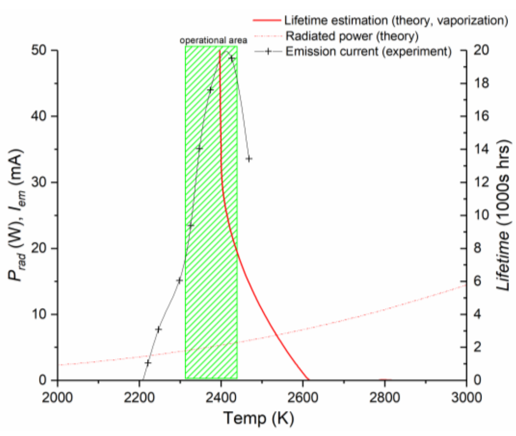


**Figure 5: Neutralizer filament emission current, radiated power and predicted lifetime (due to vaporization) as a function of temperature**

A more serious cathode life limiting factor is filament erosion due to iodine neutral gas and iodine ion bombardment, causing both direct sputtering and reactive ion etching of the filament by halogen ions. Accurate modelling is challenging because of lack of both sputter yield data for iodine ions, and iodine-tungsten chemical reactivity at elevated temperatures. Experimental measurements of the erosion rate have been made after operation of 30 and 60 hours consequently, and results are shown in Figure 6.

As it can be seen, the change in filament radius is about ten times higher than for vaporization. As the filament radius decreases, electron space-charge effects become more significant, and the effective emitted current decreases. Failure is expected when the emitted current is less than the ion beam current, which occurs when the filament radius is reduced by about 40%. Extrapolation with an empirical model shows that this corresponds to a lifetime of about 1800 hours per cathode (or a total lifetime of 3600 hours for two cathodes).

It should be noted that the cathodes are operated in a constant temperature control mode (CT), which also keeps the erosion rate nearly constant. This is achieved in the NPT30 by monitoring the cathode resistance and continuously adjusting the heating current.

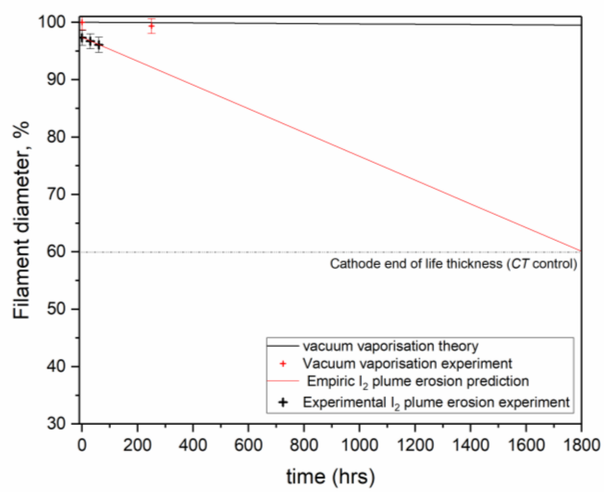


**Figure 6: Results of the filament erosion measurements due to vaporization in vacuum and interaction with the iodine plume. Plume erosion data have an original offset of about 3% due to initial conditioning procedure at high temperature (about 2500 K)**

## EXPERIMENTAL VALIDATION

A number of experimental verifications have been performed using the engineering qualification model of NPT30-I2-1U, including several studies linked to fundamental ionization and ion acceleration problems with a high level of uncertainty in the literature on iodine plasma discharges available. The mentioned experimental verifications and studies included: ion beam diagnostics with 2D profile mapping and ion energy analysis, ion beam composition analysis, plume diagnostics through the measurements of the plasma density and plasma potential in near field region, as well as direct thrust measurement campaign. As an additional valuable fundamental result of this research campaign, secondary electron emission rates due to iodine ion impact on different materials have been measured for a first time and published elsewhere[14].

### *Performance Mapping*

Propulsion system performance mapping has been obtained from the thrust and impulse measurements (plotted in Figure 7).

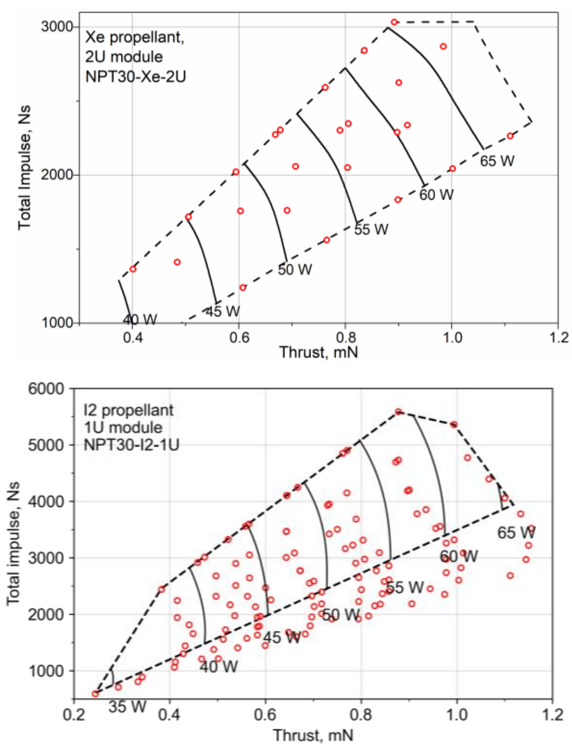


**Figure 7: Performance map of the NPT30-I2-1U, showing both experimental points and extrapolated operational window**

This performance map of the thruster, for input power values between 35W – 65W, enables the selection of thruster operation mode for flight such that the desired thrust and total impulse values are achieved. For comparison, both xenon and iodine propellant sets of data are shown. Due to the high pressurization and the low mass flow rates required, the xenon-based module with the integrated propellant storage has a total volume of 2 CubeSat units and a mass close to 2 kg, i.e. about 2 times larger and heavier than the iodine-based propulsion system NPT30-I2-1U. In total, 120 points are measured for iodine propelled system, and about 60 points for xenon one, and each point has been measured in a steady state condition at more than one hour of continuous firing with following re-validation. The area outlined by the dash line on the performance map contains the region of parameters which are considered as satisfying operational points from both system point of view (steady state temperature, internal voltage and current levels, erosion rate etc.) and performance reasoning. As it can be seen, despite the much smaller dimensions and mass, the iodine-based propulsion system provides substantial increase in the total impulse capacity which is caused by both denser propellant storage and higher ionization efficiency (and consequently specific impulse). With the NPT30-I2-1U system, a maximum specific impulse value of about 2450s is reached around 60 W of the input power (about double of what can be reached with the xenon propellant), and a maximum thrust of 1.15 mN which corresponds to about 65 W power input. More detailed view on the specific impulse measurement at various internal parameters such as an iodine flow rate and RF power delivered to antenna is given on Figure 8 below.

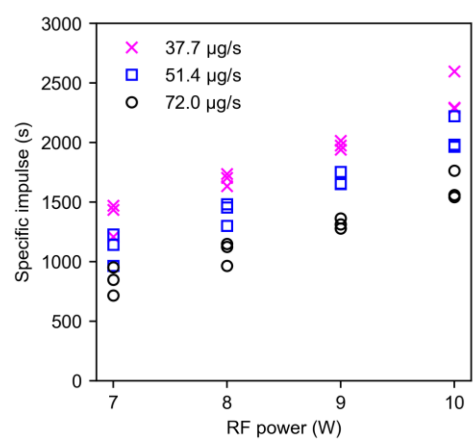


**Fig. 8. Specific impulse as a function of input RF power to discharge at different flow rates of the propellant and acceleration voltages (values not displayed)**

2-D mapping of the ion beam for different cases of thruster operation parameters have been obtained using the scanning probe array, representing angular intensity of the ion flux at 30 cm distance from the further exhaust. Example of the measured 2D plume map is shown on Figure 9. The NPT30-I2-1U beam divergence was found to change from 9 degrees to 15 degrees over the whole range of thruster operation[15]. These values are within the reported levels for common beam divergence of gridded thrusters.

### *Ion Beam Characterization*

With iodine propellant, the thruster ion beam is composed of at least three groups of ions, including I+, I2+ and I++ and a typical ion signal composition for the NPT30-I2-1U thruster is shown on Figure 10. The beam composition is known to directly affect thruster's high-level performance such as thrust and specific impulse; therefore, it is important to measure and study it. NPT30-I2-1U EQM has been used to perform these measurements as a function of the RF power on plasma exciting antenna and mass flow rate of the propellant, using the time-of-flight spectrometry[14].

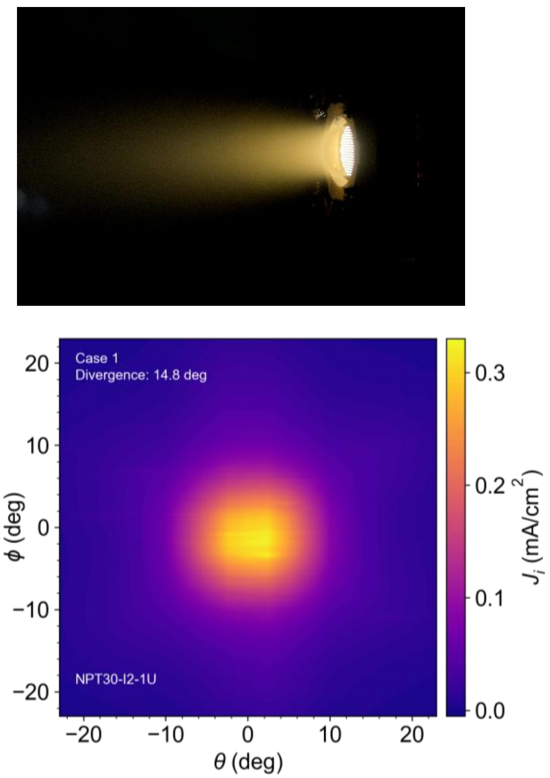


**Fig. 9: View on the plume of NPT30-I2-1U (top); Example of 2D map of the iodine plume measured at 30 cm distance from the thruster exhaust (bottom)**

Figure 11 shows the evolution of the three ion species with increasing flow rate. Beam composition has been studied as a function of other parameters, such as discharge RF power[14].

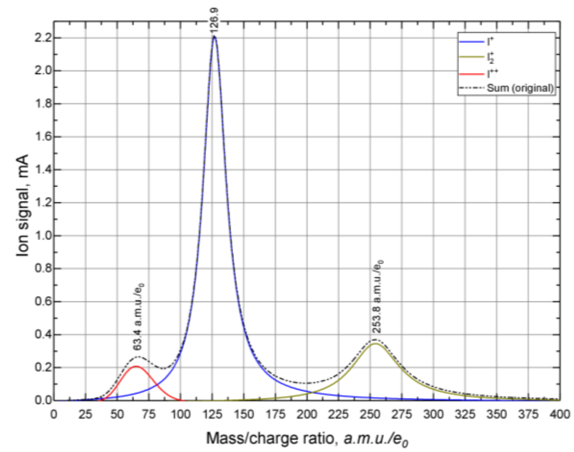


**Figure 10: Typical iodine ion beam signal composition obtained with time-of-flight spectrometry**

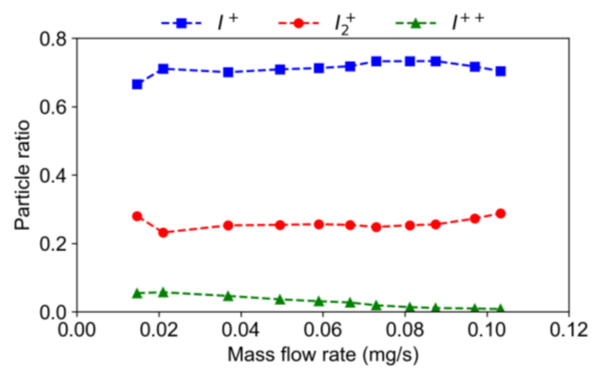


**Figure 11: Evolution of particle ratio with increase in mass flow rate**

## LAUNCH QUALIFICATION AND SPACE TESTING

### *Launch Qualification*

Launch qualification campaign of the system, which included shock, vibration, thermal vacuum, and ambient thermal cycling has been successfully completed by June 2020, and the flight unit was shipped for the integration into spacecraft. Figure 12 shows view on the propulsion system during the shock testing.

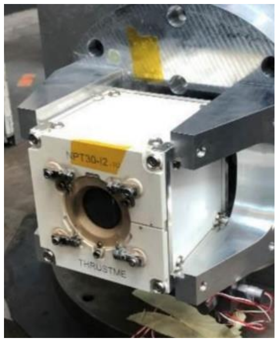

**Figure 12: NPT30-I2-1U QM attached to a shock bench setup[4]**

In parallel to the launch qualification and space testing, the radiation test campaign has been performed on separately built DUT assemblies, with the objective to perform SEE and TID irradiation tests on a complete set of NPT30-I2-1U electronic submodules with COTS electronic components. The two tests were performed on different sets of submodules. The tests gave reference values for the highest proton beam energy and the maximum total dose level that can be sustained by the system without irreversible failure, which were found to be 200 MeV and about 15 krad, respectively. It should be mentioned that the test assemblies were unshielded, while in flight configuration all power subsystems have a 1.6 mm thick aluminum shielding. All errors were logged and analyzed to find potential causes and possible preventive measures to be implemented in future designs.

### *In-flight Testing*

The propulsion system has been launched on the 6th of November 2020 onboard of a 12U platform with possibility to perform relatively long firings (up to 90 minutes) at high power for this class of platforms (50-60 W). After successful satellite commissioning, the first firing operations have been performed starting from December 2020. Multiple firings of 90 minutes each have been performed in different operational modes, having a thrust rage from 0.5 to 0.8 mN and steady power up to 55 W. The propulsion system telemetry downloaded after the firings showed correct system operation with all major parameters staying within the specified margins. An example of a firing telemetry dataset is shown on Figure 13 for one of the firing slots, demonstrating reported thrust and power profiles. As can be seen, this firing had a thrust value fixed to 0.8 mN and average input power about 52 W, and an ignition/warm-up time of about 13 minutes (including time needed for the iodine propellant heating). The mentioned firing slot resulted in an accumulated impulse of about 3.9 N·s and an orbit change of approximately 400 meters. The manoeuvres were tracked using the onboard GPS receiver, and later confirmed by NORAD TLEs. Up to the moment, 14 firings in both prograde and retrograde directions resulted in the accumulated orbit altitude change of about 4 kilometers.

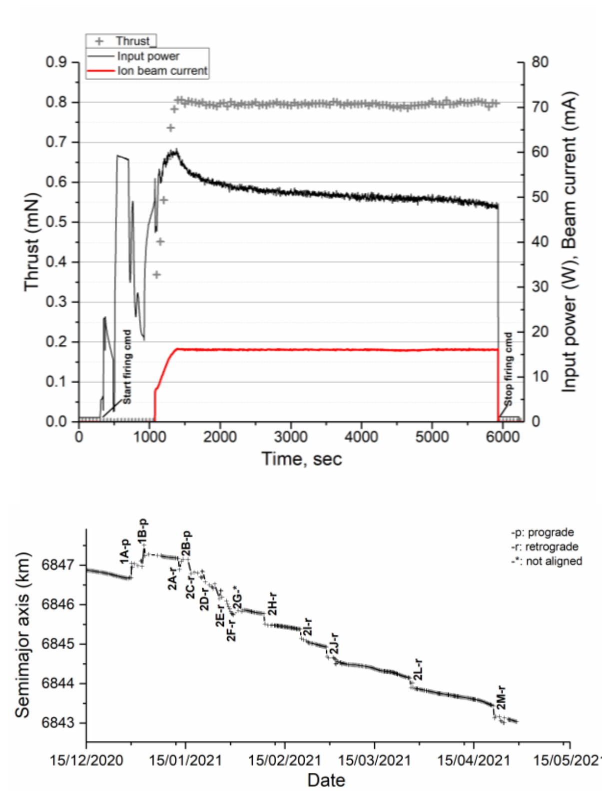


**Figure 13: Flight telemetry for the firing slot having 0.8 mN thrust target and 90 minutes cycle duration (top); satellite maneuvers tracking using NORAD TLEs for all firings until May 2021**

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