Demonstrating low-power iodine-fed Hall thruster propulsion system

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***Abstract*—A fully operational proof-of-concept iodine-fed Hall thruster propulsion system is presented. The system is developed to provide maneuvering capabilities to small platforms, operating below 250 W of total input power and providing nearly 10 mN of thrust. The fully-integrated architecture allows straightforward propulsive control. The system description, the development stage and the propulsion metrics are presented and discussed.**

***Index Terms*—electric space propulsion, iodine, Hall thruster.**

I. Introduction

To date, several thousands of Earth satellites feature an onboard propulsion system based on Hall thruster technology. These devices are key characters for in-orbit maneuvering thanks to their remarkable thrust-to-power ratio and thrust density compared to other electric propulsion alternatives. Sub-kilowatt Hall thrusters can usually operate in the excess of 50 mN/kW on xenon propellant. Though, xenon suffers from limited production offer and cost fluctuations. While it remains the preferred propellant in research laboratories and fundamental studies, the majority of commercial LEO platforms that employ Hall thrusters operates on krypton and argon propellants today. Historically, the use of relatively low mass propellants has been avoided for reasons related to fundamental ion acceleration mechanism. Besides the significant cost benefits such a system choice brings, propulsive performance is severely impacted due to the propellant nature, leading to about 40 mN/kW at best. This especially affects the low-power class of thrusters which typically feature lower thrust-to-power ratios.

In this context, the use of iodine as propellant brings unmatched advantages to electrostatic plasma thrusters, from fundamental plasma phenomena aspects to overall system performance and characteristics. This does particularly apply to propulsion systems designed for platforms below a few hundred kilograms. Iodine enables the same performance achievable with xenon at 1-2% of direct cost and about one third of storage volume thanks to its solid nature at room temperature. Systems designed to operate with iodine do not necessitate implementing valves and pipes rated for hundreds of bars - as typically required for noble gas fluidics - since the highest pressure achievable on iodine reads a few tens of mbar. This technology has already been demonstrated in space by ThrustMe [1], which currently boasts several tens of gridded ion thruster systems in orbit. As a result, combining iodine propellant and Hall thruster technology is a necessary step to ensure high performance in-space maneuvering with extremely reduced costs. Attempts in developing an iodine-based Hall thruster propulsion system have been recorded in the past [2], [3], relying however on xenon-fed cathode neutralizers and focusing on testing individual units of the entire propulsion system.

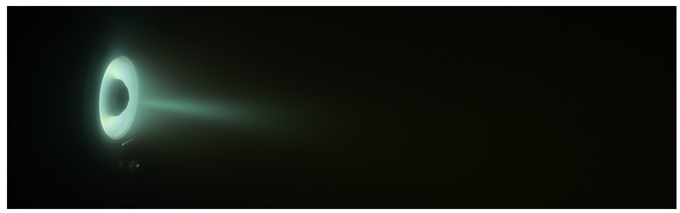

Fig. 1. Photograph of JPT150 thruster head in operation.

This paper reports on the progress results in the development of a low-power Hall thruster propulsion system operating on iodine propellant named JPT150. A proof-of-concept of the entire propulsion system is presented and the operational details are discussed.

II. JPT150 System Description

The propulsion system is designed to operate at a total nominal input power below 250 W and entirely on iodine propellant. It is conceived in a fully integrated architecture that comprises of a thruster head unit, a cathode neutralizer unit, a power processing unit, a flow control unit, and the propellant storage. It is designed to follow autonomous decision-making to provide the desired performance metric during operation, namely thrust or specific impulse, which represent the input commands. Figure 1 shows the thruster head in operation as integrated with the rest of the system components.

Every sub-unit of the propulsion system is designed and developed in-house, including both hardware and software. Full control of thruster head and cathode is performed using custom algorithms implemented over standard communication protocols between sub-units and with the main external command unit interfacing with the entire propulsion system. Each sub-unit clearly covers specific functions, e.g. propellant flow control and discharge parameters tuning. Iodine is stored in solid form in the dedicated storage system. Sublimation and distribution is handled via the flow control unit using a network of heating elements and temperature sensors. Power processing unit handles ignition and operation of both the cathode and the thruster head.

The thruster head is designed to optimize propulsive performance in the low power range. The challenge in this process involves several aspects. Propellant distribution in the plasma channel is carefully addressed to enhance propellant utilization efficiency and discharge stability [4]. The magnetic field topology, achieved using only permanent magnets, is carefully designed to exploit the magnetic lens principle such that plume divergence and wall erosion phenomena are minimized. The plasma discharge channel dimensions are sized to especially enhance performance at the desired discharge power. The cathode neutralizer is designed to exploit the plasma-bridge principle to supply electrons to the thruster head for sustaining the discharge and to the plume to neutralize the ion beam. It operates on iodine propellant, with a mass flow rate and power that are both a fraction of those required by the thruster head. At early stages of the system development, filament cathode were used to support rapid prototyping [5].

III. Testing Setup Description

Experimental tests are conducted at ThrustMe premises, in the largest iodine-compatible vacuum facility currently in Europe, with a chamber diameter of 1 m and length of 2 m. Background pressure in the order of 1E-6 mbar is ensured by a system of turbo-molecular-primary pumps in combination with a cryogenic pump leading to an effective iodine pumping speed in the order of a few thousands of L/s. During thruster operation, facility pressure reads about 2E-5 mbar.

Thrust measurements have been performed using a folded pendulum balance [6], [7]. This balance architecture is characterized by its dynamic response in the order of 1 Hz or less. The system consists in a plate suspended by a simple pendulum on one end and by an inverted pendulum on the other. The suspended plate represents the thruster mounting location. Flexible elements allow translation of the support plate along the thruster z axis. A force gauge is used to directly infer the thrust generated upon calibration. The latter is performed by employing a calibrated linear compression spring with elastic constant of 10 mN/mm pushing on the thruster central pole along its axis. The spring displacement is manually controlled via a precision translation stage with 10 um resolution. The entire setup is carefully aligned for the purpose of calibration and measurements using a laser-cross pendulum. The thrust balance shows a linear response in the range 0.2-15 mN with a detectable resolution smaller than 0.05 mN. Net thrust due to ion acceleration is directly measured from the sudden drop in force signal occurring as the anode voltage is manually turned off.

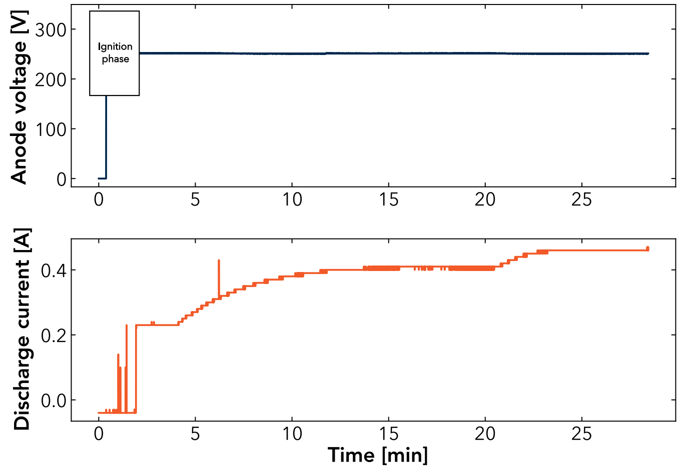

Fig. 2. Instance of discharge telemetry profile. (top) Anode voltage, (bottom) anode current.

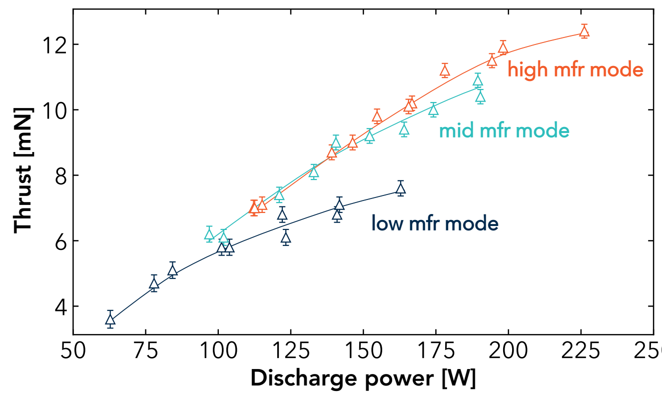

Fig. 3. Thrust versus discharge power.

IV. Results and Conclusion

Figure 2 shows an instance of thruster telemetry that includes the ignition phase and continuous firing in terms of anode voltage and discharge current. The thruster ignition algorithm is tuned according to the predefined mass flow rate. This specific instance shows ignition at a particularly low mass flow rate, resulting in 0.23 A of discharge current. This test was performed during a ignition reliability test campaign to qualify the ignition process at different mass flow rates. A few minutes after ignition, the propellant flow rate is intentionally increased targeting more typical operation modes. In this test, the anode voltage is kept constant at 250 V. Once steady state at 0.4 A is reached after about 20 minutes of firing, a further increase in discharge current is targeted. Operation at more than 0.6 A is readily possible from a discharge stability and

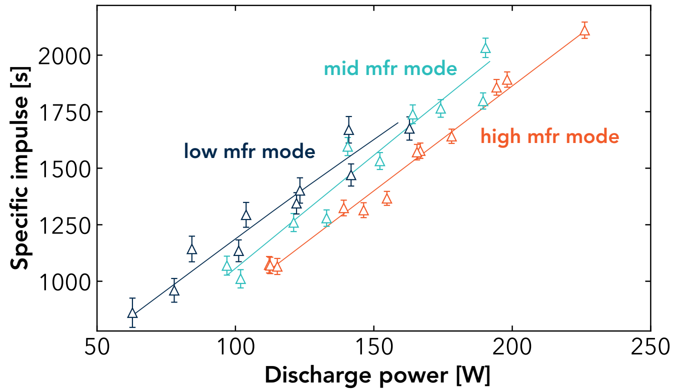

Fig. 4. Specific impulse versus discharge power.

thermal constraints points of view. This relatively large range of operating currents directly correlates with a broad spectrum of possible thrust values.

In general terms, the current version of the entire propulsion system under development and testing shows full operational versatility in the range 50-250 W of thruster head power, with a delivered thrust roughly spanning from 4 mN to 12 mN. Figure 3 shows the thrust profiles at different qualitative mass flow rates as function of the net discharge power. From these experimental values, it is retrieved that thrust-to-power ratios of the thruster head alone exceeds 60 mN/kW, with specific impulse reaching up to 2000 s, see Figure 4.

The cathode neutralizer can reliably operate on iodine propellant providing the required electron current to sustain and neutralize the ion beam. In any operating mode, the cathode requires less than 10% of the thruster head mass flow rate and it consumes only a minor fraction of the total input power. The power processing unit and flow control unit also show successful functioning demonstrated over tens of hours of operation and hundreds of cycles, completing the objective of developing a fully integrated system.

At the time of writing, the thruster head and the cathode have cumulated more than 100 hours of independent operation testing, achieved under several conditions to explore the full operating envelope. The system integrated as a whole has operated for several tens of hours, targeting hundreds in the short future. Test results from the cumulative firings, which correspond to more than 3 kNs of demonstrated total impulse, prove the competitiveness of JPT150 system for its power class. Further development steps are being addressed in order to achieve all qualifications needed for in-orbit operation.

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