REGULUS: Iodine Fed Plasma Propulsion System for Small Satellites

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Abstract: REGULUS is a complete electric propulsion unit fed with iodine propellant that is under development at Technology for Propulsion and Innovation[21], an Italian based company developing propulsion systems. REGULUS relies on the Magnetically Enhanced Plasma Thruster (MEPT) which is integrated with electronics, fluidic, and thermos-structural subsystems into a complete propulsion unit of 1.5 U with a total mass below 3 kg. REGULUS has been designed specifically for CubeSat platforms ranging from 6U up to 150 kg satellites, and for CubeSat carriers. It is conceived to be a "Plugged & Played" to avoid difficult integration procedures, and it is built without relying on space-grade qualified components to reduce the recurring costs. It will provide 0.6 mN thrust and 600 s specific impulse at 50 W of input power and a total impulse up to 3000 Ns. An expanded version of 2U is also being developed, with a total impulse of about 11000 Ns. REGULUS will perform an In-Orbit Demonstration (IoD) onboard UniSat-7. In this work we will go through the design of the REGULUS platform. The performances of the MEPT operated with xenon and iodine propellants have been compared. Moreover, the subsystems of REGULUS have been described and qualification tests are presented.

I.introduction

SmallSats, including CubeSats[1], have become increasingly common in recent years because of their extremely reduced cost with respect to traditional satellites. In the near future, the arrival on the market of large SmallSat constellations will have a disruptive impact on many sectors, from natural disaster monitoring and recovery to the development of the "internet of the things"[2,3]. Nevertheless, the key factor to spread SmallSat technology is the development of ad-hoc propulsion systems which can enable increasingly complex missions where orbit positioning and maintenance are required[4,5]. Clearly, the integration of a propulsion system into a SmallSat is extremely challenging because of the strict mass, volume, power and cost budgets[4] involved and the intrinsic complexity of a space thruster. As a consequence, the number of missions involving SmallSats equipped with propulsion units is still limited, even though rapidly increasing[5]. An example is the 1.5 U BRICSat-P launched in 2015, where four μCAT thrusters[6] were employed to detumble the satellite. Other examples are the STRaND-1[7,8] and the SERPENS[9] missions. In the former, launched

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in 2013, a 3U CubeSat carried a Pulse Plasma Thruster (PPT) for orbital corrections and a water-alcohol resistojet for attitude control; in the latter, launched in 2015, a 3U CubeSat used a PPT to counteract orbital decay caused by atmospheric drag. Finally, in 2018 the first In-Orbit Demonstration (IOD) of e Field Emission Electric Propulsion (FEEP) was accomplished[10]. The IFM Nano Thruster developed by the Austrian company Enpulsion[11] was integrated in a 3U CubeSat and exploited to change the semi-major axis (i.e., tens of meters) of a Low Earth Orbit.
Recently, many studies have investigated the use of iodine as propellant for electric thrusters designed for SmallSats[12-15]. In fact:

- Iodine can be stored in solid state and, in turn, it is three times denser than xenon[16]; this allows to have a higher total impulse with the same volume.
- Iodine can be stored at moderate temperature (e.g., ambient temperature) and pressure (e.g., atmospheric pressure), so no cryogenic or strict thermal control is required[12]
- Iodine has low procurement cost: 90% less than xenon[13]
- Iodine suffers no transportation issues as the tank is not pressurized, therefore the entire subsystem can be shipped to the launch platform ready for use.

Another advantage of the iodine adoption is that, from a propulsive standpoint, its performances are similar to the ones obtained with xenon propellant; this has been proven for ion and hall-effect thrusters[13,17]. Given all these advantages, the use of iodine propellant might be the key factor to enhance the adoption of propulsion systems in SmallSats. Nonetheless, an iodine-based system is not without its challenges: (i) the entire device must be kept at relatively high temperature (< 100 °C) in order to avoid the obstruction of the fluidic line due to the condensation of the propellant[12], and (ii) iodine can be very reactive, therefore materials must be properly selected in order to avoid chemical corrosion[18]. Some of the missions in which the adoption of an iodine-based propulsion system has been planned are iSat[12] and Lunar iceCube[19]. iSAT is a small satellite demonstrator designed and built at NASA's Marshall Spacecraft Center; the mission was initially planned for launch in fall 2017, then later moved to mid-2018, until in May 2017 the project was temporarily suspended to allow the maturity of the propulsion system to increase. Lunar iceCube is instead a 6U CubeSat propelled by a 60-W RF ion thruster whose mission scope is the lunar surface observation, and the launch is planned for 2021.

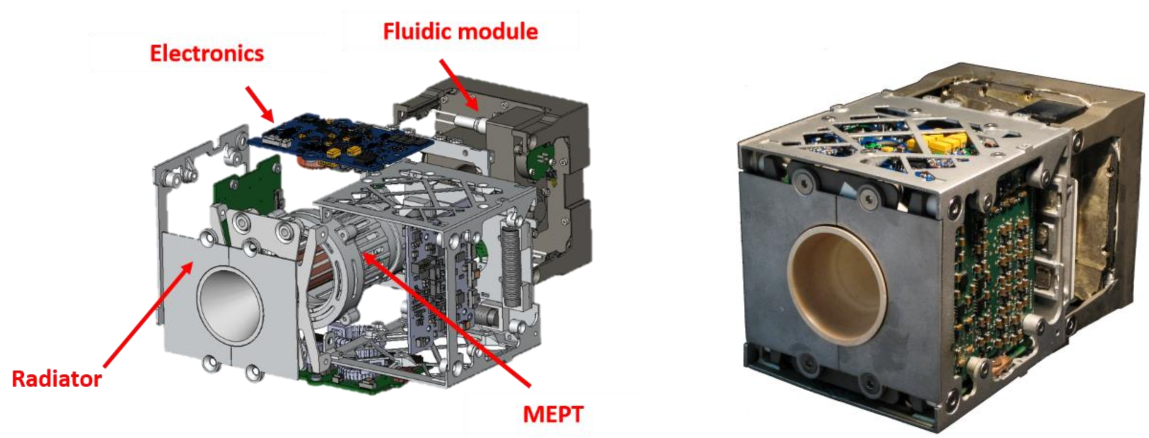

Figure 1: Rendering and picture of the REGULUS propulsion unit. Highlighted the subsystems of the module.

In this frame, the REGULUS platform[20] has been conceived and designed. Specifically, REGULUS is a complete electric propulsion unit fed with iodine propellant that is under development at Technology for Propulsion and Innovation (T4i)[21], an Italian based company developing propulsion systems. REGULUS technology relies on the Magnetically Enhanced Plasma Thruster (MEPT) which is integrated with electronics, fluidic line, and thermos-structural subsystems into a complete propulsion unit of 1.5 U (see Figure 1), with a total mass which is below 3 kg. REGULUS has been specifically designed for CubeSat platforms ranging from 6U up to 150 kg satellites, and for CubeSat carriers.

It is conceived to be "Plugged & Played" to avoid difficult integration procedures, and it is built without relying on space-grade qualified components to reduce the recurring costs. It will provide 0.6 mN thrust and 600 s specific impulse at 50 W of input power, and a total impulse up to 3000 Ns. An expanded version of 2U is also being developed, with a total impulse of about 11000 Ns. REGULUS will perform an In-Orbit Demonstration (IoD) onboard UniSat-

7[22], a microsatellite operated by the Italian company GAUSS. The launch will take place during Q2/Q3 2020 using a Soyuz-2 launch vehicle. The complete objectives of UniSat-7 mission are to inject several satellites into a 550 km height Sun Synchronous Orbit (SSO) and to act as a technology demonstrator to test specific payloads (as REGULUS) which will be used in subsequent GAUSS CubeSat missions. In particular, REGULUS primary objective is to demonstrate its capability to enhance Unisat-7 mission scenarios, enabling maneuvers such as drag compensation and semi-major axis variation. At the moment, we are manufacturing the Qualification Model (QM) and the Flight Model (FM) of REGULUS, that should be delivered by the end of 2019 for the IoD.
In the current work we will go through the design of the REGULUS platform. In particular, in Section II the performances of the MEPT operated with xenon and iodine propellants are compared. In Section III the subsystems of REGULUS, namely electronics, fluidic, and thermo-structural are illustrated, along with qualification tests. Finally, conclusions are drawn in Section IV.

II.Magnetically Enhanced Plasma Thruster

The MEPT is a cathode-less RF thruster[23] specifically designed for CubeSat propulsion (see Figure 2). The cathode-less concept is a relatively new technology which is particularly suited for CubeSat propulsion solutions thanks to its simple design. Specifically, the main components of a cathode-less thruster are: (i) a dielectric tube inside which the neutral gas propellant is ionized, (ii) a RF antenna working in the MHz range which provide the power to ionize the gas, and (iii) magnets which produce a magneto-static field that enhances the plasma confinement[24] and provides the magnetic nozzle effect[25] downstream the source exhaust. The principal features which make a cathode-less thruster suitable for CubeSat propulsion are: (i) a very simple structure, which helps limit the cost of the system; (ii) absence of electrodes immersed in the plasma; (iii) adaptability to different propellants by simple geometric reconfiguration; (iv) no need for a neutralizer because the ejected plasma is neutral.

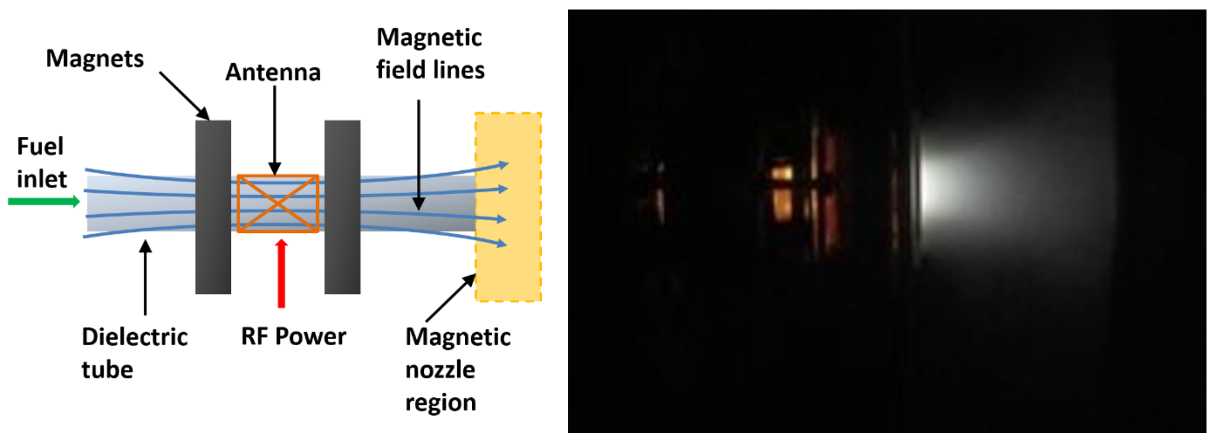

Figure 2: Schematic and picture of the MEPT mounted on board of REGULUS. In the picture, the thruster is operated with iodine propellant.

The performances of the MEPT, operated with both xenon and iodine propellants, have been measured at the CISAS high vacuum facility, where the thruster has been tested inside a 2 m long cylindrical vacuum chamber with an inner diameter of 0.6 m[26]. The RF power has been provided to the thruster by a Spin HFPA-300 linear amplifier (1.8-30~MHz, power up to 300~W) driven by an HP 8648B signal generator and connected to the MEPT via a coaxial power line. Xenon was provided by an MKS 1179B flow controller, connected to a pressurized reservoir, while iodine was provided to the prototype through a feeding system, composed of a heated tank and a manifold containing valves and flow control orifices[27]. The equipment employed for the characterization of MET includes a thrust balance, specifically designed for RF thrusters of small-to-medium size[28], and RF probes for vector voltage and current measurement[20]. Considering the accuracy of each instrument, along with the uncertainty introduced by the iodine feeding line, the confidence interval associated to the measurements is: (i) ±15-20% for thrust, (ii) ±10% for the power provided to the MEPT, along with (iii) few percent points for the xenon mass flow rate, and ±10-15% for iodine.
In Figure 3 the propulsive performances (i.e., thrust T and specific impulse I_{sp} as a function of the power Pw) have been depicted. MEPT has been operated with a 0.1 mg/s mass flow rate of both xenon and iodine propellants. The RF

antenna working frequency was 2 MHz and the input power Pw has been varied in the range 15-60 W. During the test session, the vacuum chamber pressure was maintained at 10^{-5} mbar. The thrust and the specific impulse are linear functions of power, for both propellants. In particular, propulsive performances are roughly 15-20% lower if MEPT is operated with iodine instead of xenon propellant. Although, in the case of iodine, a wider margin of error in respect to xenon must be assumed, due to the uncertainty associated with the flow control method. Therefore, we can conclude that iodine is a valid candidate to be exploited in real-life space missions provided its good propulsive performances.

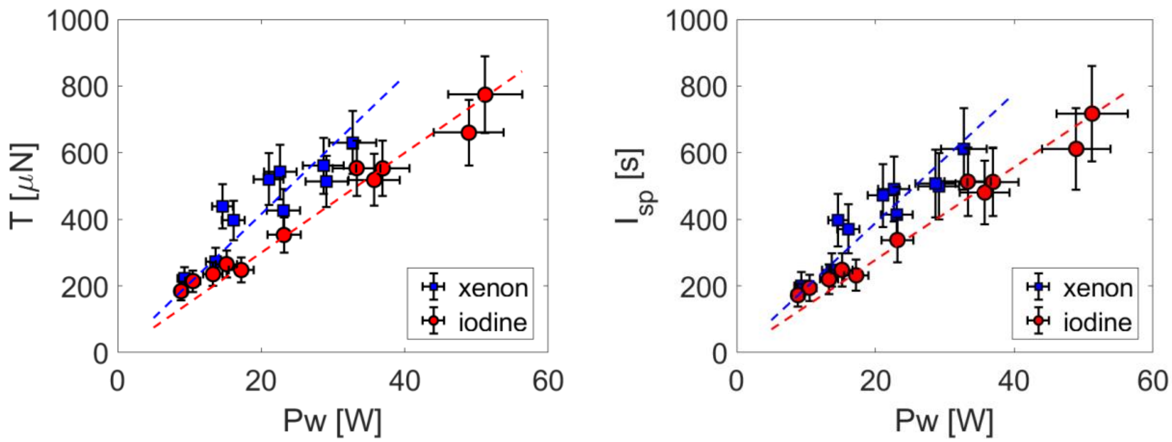

Figure 3: Propulsive performances evaluated when the MEPT is operated with xenon or iodine propellant. Thrust T, and specific impulse I_{sp} as a function of the input power to the thruster Pw. Operation mass flow rate $\dot{m}_0 = 0.10$ mg/s.

III. REGULUS subsystems

A. Electronics

In order to be competitive with the costs and the standards of reliability imposed by the market, the electronics have been designed to be compliant with European Cooperation for Space Standardization (ECSS) for Components Off-The-Shelf (COTS) as suggested by ESA in the CubeSat environment.

In general, the choice of COTS can be tailored to the customer needs by means of dedicated risk analyses. Moreover, the test and the reliability plans consider the requirements of compatibility of COTS also with the expected radiation environment (depending on orbit and mission duration). Nonetheless, considering the duration of typical missions (3-5 years) and the candidate orbits (LEO around 400 km of height), calculation with SPENVIS[29] show that the Total Ionization Dose (TID) is not particularly demanding. In particular, using the approach of careful COTS design sequence of Sinclair *et al.*,[30] and considering ECSS_E_ST-10-12C along with the three classes identified by ECSS-Q-ST-60C, we can choose COTS which can be compliant with the total dose for the IOD planned with Unisat-7. In fact, Sinclair suggests that it is possible to choose some elements over 30 krad tolerant using his "Careful COTS design sequence".

A test campaign to verify the compliance to radiation effects is planned in radiation hardness assurance test facility in accord with ESCC-22900.

1. Interface

The interface with the satellite involves four connectors (different in size and number of pins to avoid mistakes):
- Two separate communication lines (primary and secondary) with two redundant CANbus and one I2C[31] protocols
- One power connector for the regulated 12V DC
- One connector for the safety, which will be an "insert before flight" type device.

The connectors are fixed on two Printed Circuit Boards (PCBs) needed for the fixture to the structure. In any case, the JTAG connector[32] for the last-second programming is easily reachable also during integration.

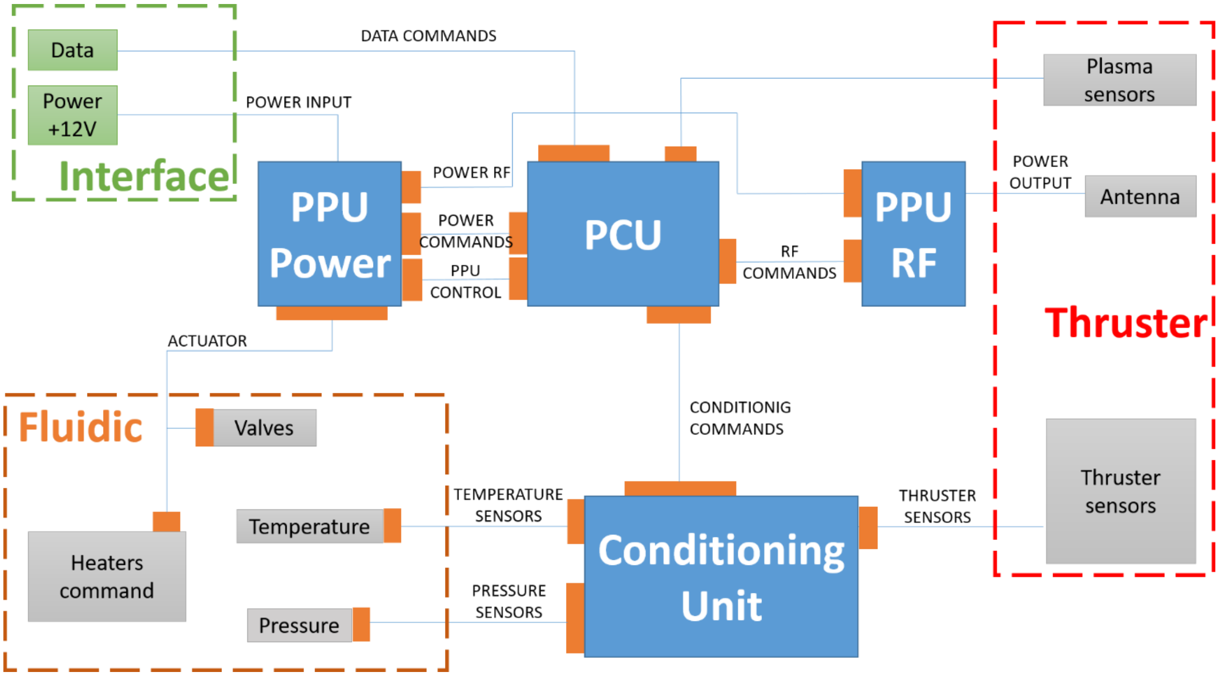

Figure 4 Schematic of the electronics subsystem of REGULUS.

2. *Layout*

The layout will be divided in four different boards positioned around the main thruster with suitable isolation and protection. The schematic of the electronics subsystem of REGULUS is depicted in Figure 4; the four boards consist of:

- **Power Control Unit (PCU)** which controls and monitors the functioning of MEPT; at the same time the PCU is the interface with the spacecraft via CAN bus and/or I2C. It performs the following main functions:
    - Interface with spacecraft for the data link
    - Interface with Analog to Digital Converter (ADC)
    - Receive telecommands and send telemetries
    - Command valves with peak and hold strategy
    - Command Pulse-Width Modulation (PWM) for heathers
    - Perform thermal control
    - Run algorithms for thruster switch on and off sequences
    - Monitor health status of the thruster
    - Manage the faults (FDIR)

    The onboard microprocessor has a well-established space heritage, having been used in several missions. Moreover, the PCU is reprogrammable in flight using a self-programming capability through bootstrap functionality and an external flash memory on which it will be stored the new software sent via data link. If the main satellite requires thrust at different power other than 50W in a range between 30 and 60W the system can adapt its configuration to perform a constant power thrust at the desired level.
- **Conditioning Unit** controls the diagnostic signal conditioning.
- **Power Processing Unit (PPU) - Power** provides DC power supplies for the auxiliary subsystem of the thruster and the conditioning of controllers as valves and heaters.
- **PPU-RF** power unit which is the main power segment where the DC voltage is converted in RF to supply the power to the thruster. The Electro-Magnetic Compatibility (EMC) of this device is tested considering the ECSS requirements.

3. *Software*

The FreeRTOS[33] is used for managing all the tasks required, controlling the thruster and communicating with the satellite through CANbus or I2C using the Cubesat Space Protocol (CSP).

B. Fluidic line

The fluidic subsystem of REGULUS (see Figure 5) has the objective of delivering a pre-determined mass flow rate when the motor is activated. The mass flow must be constant within a ±5% of nominal rate in order to obtain the required motor performance and efficiency throughout the lifespan. As shown in Figure 5, the fluidic subsystem is composed of a tank, a flow regulator, and an injector. The entire subsystem is fabricated with additive manufacturing technologies to comply with the strictest volume and mass budgets. All components that are wetted by the propellant (in both solid and gaseous state) are made of materials that present very high chemical compatibility with iodine, for instance Nickel superalloys such as Inconel and Hastelloy, whereas FKM, FFKM, and PTFE[34] sealing is used at the fluidic interfaces. The tank is filled with solid iodine propellant and can be designed bigger (or smaller) independently from the rest of the fluidic system. In REGULUS, the tank module has also a structural purpose: the four "legs" that stretch from the tank are used to fix the entire subsystem to the rest of the motor structure. When the tank is heated, the iodine in gaseous state enters the flow regulator module, which is the technologic core of the fluidic subsystem. It has the delicate duty of maintaining the mass flow rate constant while the motor is thrusting by means of a pair of actuators and pressure and temperature transducers. The injector serves for two different purposes: the first is to increase the thermal resistance between the hot motor and the fluidic subsystem and the second is, naturally, to deliver the iodine inside the motor, where it is turned into plasma.

The entire subsystem is thermally controlled through a closed-loop control, using several temperature transducers and two thin-foil heaters. The thermal control is used to (i) sublimate the solid iodine into gas, (ii) perform a coarse control of the mass flow rate, (iii) to avoid the re-condensation of the iodine along the fluidic line, and (iv) to keep the temperature below the maximum threshold to avoid the electronic components from over-heating failures and to avoid the liquid state of the iodine ($T < 115°C$ everywhere). Moreover, the fluidic subsystem has a connector that it is used as electronic interface to the electronics.

Finally, it is worth highlighting that functional tests have been performed[27] to verify the capability of the fluidic line to provide a 0.1 mg/s mass flow rate with a stability of ±5%. Successful results in vacuum and at ambient temperature (20-30°C) have been obtained; other tests in a variable temperature environment (-40°C/+80°C) are currently ongoing.

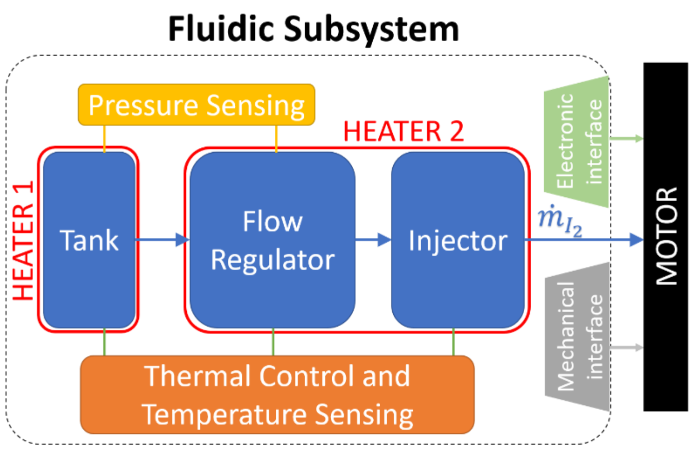

Figure 5:Schematic of the fluidic line of REGULUS.

C. Thermo-structural

The scope of the thermo-structural subsystem is to accommodate all the modules of the propulsion unit, such as electronics, fluidic line and MEPT. Moreover, it has the function to dissipate the heat generated to the propulsion system in order to allow each component to work in the correct temperature range.

The main drivers that guided the design of the thruster are to minimize the mass and the dimensions of the system in order to maintain the former lower than 3 kg and the latter within 1.5 U. About that, the 3D printing manufacture process has had considerable importance in achieving these goals for two reasons: the first one is that it allowed us to create shapes that would be impossible with traditional manufacturing process. The second reason is that 3D printing enabled us to reduce bolted junctions with a consequent increase in the reliability of the system. The principal thermal and mechanical requirements are summarized in Table 1.

Table 1: Thermal and mechanical requirements considered in the design of REGULUS.

Thermal requirements	Mechanical requirements
1. The system shall withstand an operative temperature environment of –25 °C - +70 °C; 2. The propulsion unit shall operate with at least 60 W input power; 3. The system shall use only one heat dissipation panel mounted on the nozzle exhaust face; 4. The Electronic temperature shall not exceed +85 °C; 5. The Fluidic temperature shall be maintained al 90 °C during firing operations.	1. The first natural frequency of the system higher than 200 Hz; 2. The system shall be compliant with the launch environment of the main launch system such as PSLV, Vega, Falcon 9 Ariane 5 and Soyuz[35]; 3. The propulsion unit shall fit the main Cubesat structure such as Gomspace, ISIS and Endurosat[36,37].

To be compliant with the first two structural requirements, the thruster has been designed with a mix of materials able to guarantee high strength, stiffness and lightness such as Scalmalloy and Ti-6Al-4V[38]. To comply with the third structural requirement, an interface module has been created that shall allow all mechanical, thermal and electrical connections. The interface can be substituted depending on the chosen Cubesat structure. REGULUS design has been verified by means of both analytical calculations and FEM (Finite Element Method) analysis performed with Ansys[39] software. Moreover, sinusoidal and random vibration tests have been performed on the EM model of the thruster in the facility of CISAS at Padova University considering the Random spectra of the Soyuz launcher (see Figure 6). We have seen a good correspondence between the results of FEM simulations and the real behavior of the thruster. After the vibration tests, the different sub-systems have been inspected and functional tests have been performed; since we do not have detected any failure, both structural and functional, we can conclude that the mechanical design is complete. The results shown a first natural frequency of the unit higher than 250 Hz and good margin of safety against breakage.

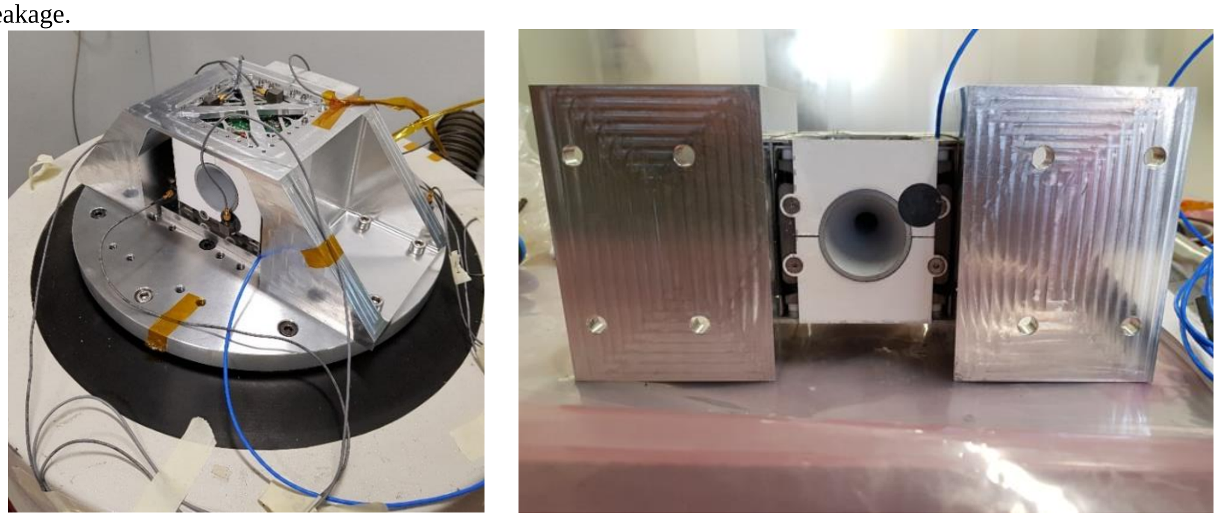

Figure 6: Mechanical vibration test of the Electro-Magnetic model of REGULUS.

About the thermal subsystem, two different thermal paths (see Figure 7) have been designed in order to handle the very different requirements of REGULUS' components. The two paths are isolated one to the other with apposite low emittance coatings. The high temperature path puts in communication the MEPT (where the main part of the thermal power that needs to be dissipated is generated) and the radiator that can dissipate the heat in the space. The low temperature path includes the electronics and the fluidic line. In the latter case, the heat produced by the electronics and the heaters of the fluidic line is dissipated through the interface to the CubeSat. A FEM model has been created to verify the thermal model considering two scenarios: (i) the Worst Hot Case (WHC), namely Cubesat at 70° C and solar flux present, along with (ii) the Worst Cold Case (WCC), namely Cubesat at -25° C and no solar flux. An input power from the bus of 60 W and a solar input power of about 3 W have been considered to be dissipated. The results of the analysis are shown for the WHC in Figure 7 (temperature distribution) and in Table 2 (temperature of the main critical component). Moreover, a Lumped Parameter Model (LPM) has been created with Octave[40] software in order to obtain preliminary results in a shorter time. The two models have shown good accordance. Considering that. with a FEM analysis that takes into account also the radiation thermal exchanges. the error can be of the order of 5-10% (i.e. 5° C - 10° C), the requirements are satisfied. In particular, we can see that the fluidic subsystem needs to be heated also in the WHC. Finally, thermal balance and thermal bake out tests have been successfully performed to validate the numerical model of the system and to verify that the propulsion unit is able to survive to the thermal environment during thrust operations.

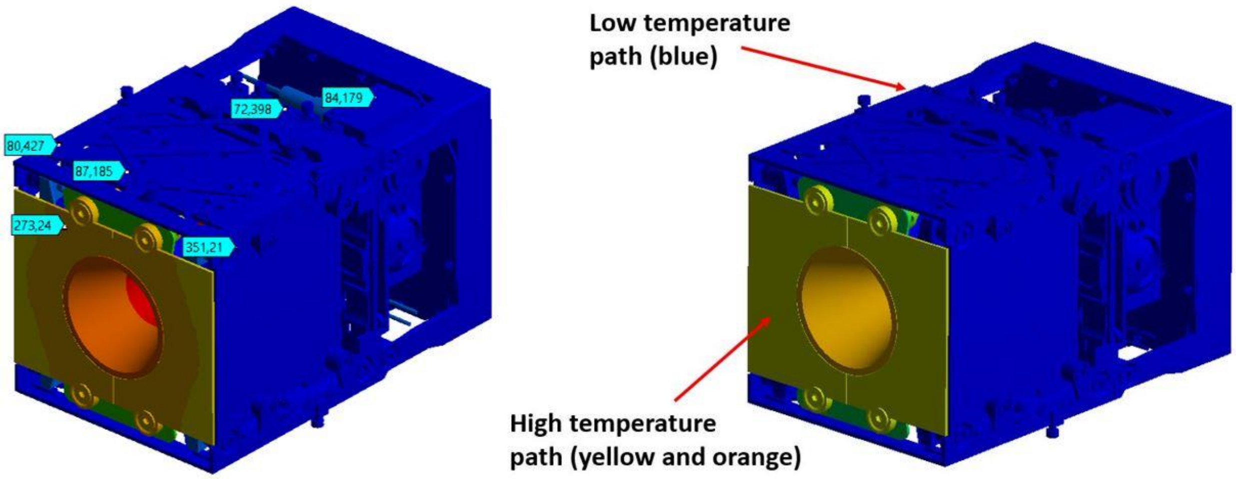

Figure 7: WHC temperature distribution (left) and thermal path (right).

Table 2: WHC maximum temperature of the most critical components; comparison between Finite Elements Method (FEM) and Lumped Parameters Model (LPM).

Component	Temperature [°C] – FEM model	Temperature [°C] – LPM model
Discharge chamber	355	351 (-1,1%)
Radiator	273	279 (+2,2%)
Electronics	87	90 (+3,4%)
Fluidics	84	92 (+9,5%)
Frame	85	87 (+2,4%)
Interface	73	75 (+2,7%)

IV.Conclusions

In this paper we have illustrated REGULUS, which is a complete electric propulsion unit fed with iodine propellant. REGULUS has a mass below 3 kg and an envelope of 1.5U; it is intended to propel satellites ranging from 6U CubeSats up to 150 kg SmallSats, and for CubeSat carriers. REGULUS integrates the MEPT with its subsystems, namely electronics, fluidic line, and thermos-structural. First, the MEPT concept has been illustrated and the thruster tested with both xenon and iodine. The two propellants have shown comparable performances, and that 0.6 mN thrust and 600 s specific impulse can be achieved at 50 W input power if MEPT is operated with iodine. Second, the subsystems (i.e., electronics, fluidic line, and thermos-structural) have been described and some qualification tests have been discussed. More specifically, the electronics performs the control and conditioning of the overall system communicating with the bus via CANbus and/or I2C via CSP protocol. Functional tests have been performed on the fluidic line in vacuum and at ambient temperature (20-30°C); the testing campaign in a variable temperature environment (-40°C/+80°C) is currently ongoing. In addition, REGULUS has successfully undertook sinusoidal and random vibration tests, along with thermal balance and thermal bake out. Finally, the qualification tests on REGULUS will be completed by October 2019, subsequently a Flight Model will be manufactured and delivered by December 2019. An IoD is planned by Q2/Q3 2020 on board Unisat-7.

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