Status of Research Activities on Electric Propulsion at CIRA

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Abstract: Electric Propulsion (EP) is widely proposed for a large number of different applications from high altitude orbit raising to orbit transfer or high impulse interplanetary scientific missions. Research on disruptive technologies or consolidation of current ones, both for low and high power class thrusters (in single or clustered configurations) requires huge efforts in terms of experimental activity, characterization and qualification before the final integration in the space applications. Given this background, CIRA established a research program on EP topics. One of the goal consists into the realization of facilities, featured by adequate sizes and equipment to enable tests of next future electric thrusters, starting from Hall Effect thrusters, and launch R&D activities related to design, and testing in this strategic field. The present paper gives an overview of CIRA development plan status of IMP-EP Program; it includes the goals achieved with a particular focus on the installation and start-up phases of the MSVC simulator as well as on thruster development and realization ones.

Nomenclature

BELSPO	=	Belgian Science Policy Office
BNC	=	Bayonet Neill Concelman
CDTI	=	Centro para el Desarrollo Tecnológico Industrial
CHD	=	Cold Head Devices
CNES	=	Centre National D'Etudes Spatiales
D-LIF	=	Doppler Laser Induced Fluorescence
D-SUB	=	D-Subminiature
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt
EP	=	Electric Propulsion
ESA	=	European Space Agency
FEM	=	Finite Element Method
FIR	=	Far Infra-Red
GEO	=	Geostationary Earth Orbit
GN_2	=	Gaseous Nitrogen
He	=	Helium
HET	=	Hall Effect Thruster
HSI	=	High Speed Imaging
IMP-EP	=	CIRA program on electric propulsion
λ	=	Magnetic stream function
L_aB_6	=	Lanthanum hexaBoride

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LETherM	=	Lumped Elements Thermal Model
LSVC	=	Large Scale Vacuum Chamber
MIR	=	Medium Infra-Red
m_n	=	Neutral mass
MHV	=	Medium High Voltage
MPD	=	MagnetoPlasmaDynamic thruster
MSVC	=	Medium Scale Vacuum Chamber
NASA	=	National Aeronautics and Space Administration
NIR	=	Near Infra-Red
OES	=	Optical Emission Spectroscopy
PIC	=	Particle in Cell method
RGA	=	Residual Gas Analyzer
SEP	=	Solar Electric Propulsion
TA	=	Test Article
UKSA	=	United Kingdom Space Agency
UPS	=	Uninterruptible Power Supply
UV	=	Ultra Violet
VIS	=	Visible Spectrum

I. Introduction

Electric Propulsion has been tested in flight in the framework of US and Soviet Union Space Programs from the second half of XXth century[1]. Taking into account the undeniable advantages, relying on high reliability, flexibility and efficiency, the number and type of EP applications have constantly expanded until becoming nowadays a valid alternative solution to chemical thrusters for spacecraft propulsion, even as primary source. For example, several commercial and institutional satellites and missions have been actually launched by exploiting cost savings, provided by EP. Electric Propulsion is widely recognized as a potential candidate not only for secondary propulsion but also for primary propulsion, applied to space missions, requiring large delta-v values. In the future, a rising demand for EP applications has been depicted by several scenario analyses[2, 3] pointing at the maturation and even achievements of EP technologies. Increasing performances in terms of rising high specific impulse, accompanied by long running times or large radii of action, have attracted the attention for the application in missions like interplanetary transfers or attitude control and positioning. It is possible to achieve significant fuel savings together with mass reduction and add other advantages in terms of multiple ignitions strategies, thrust modulation and increase spacecraft reusability[4, 5]. However, further efforts are needed in order to overcome some open points, linked to theoretical and technological issues; in this way, the goal of improving the availability, efficiency and power extension of EP systems can be reached.

Within this field, Italy claims a recognized heritage at research and development level as well as on the manufacturing side and intends to go further with playing as one of the major actors in the EP panorama. Significant efforts, oriented to extend and even improve the national system capabilities in terms of design, manufacturing and testing topics, have been provided in recent years. A crucial point is represented by the improvement in terms of availability of modern dedicated test facilities in order to support basic research activities, on one hand, and, in the other one, enable extended campaigns of characterization and qualification. This point is very important to reduce risks and costs before the integration in the final spacecrafts.

Given the background and the aforementioned motivations, CIRA (the Italian Aerospace Research Center), endorsed by ASI (the Italian Space Agency), has presented a detailed development plan, aiming at supporting the National and even European scientific community and private commercial companies in R&D activities. The primary object consists into contributing to the maturation of current technologies, starting from HET field by improving the availability of state-of-the-art facilities. In this way, also the cooperation with the international scientific community will be encouraged and the participation to the most important programs will be promoted. According to the plan, two main facilities have been proposed and they are characterized by different sizes:

- a) Medium Scale Vacuum Chamber (MSVC), i.e. 2 m of diameter and 4.5m long simulator;
- b) Large Scale Vacuum Chamber (LSVC), a world-class test facility, i.e. 8 m of diameter and 16m long simulator.

The former infrastructure has been installed in CIRA in July 2019 and will allow for the implementation of first testing capabilities at CIRA, being devoted to the preliminary studies on laboratory engines, characterized by power up to 5 kW; the latter one will be realized by the end of 2023 and it has been conceived to support the development activities oriented to next future EP, characterized by high power thrusters. The facility has been supported by design and testing (including diagnostics set-up) capabilities of thrusters and numerical support development activities.

II. Background and Trends

Space electric propulsion can serve multiple purposes[6,7]. For example, scientific observation missions of space and Earth are becoming more and more challenging in terms of requirements, demanded to propulsion systems. A strong impulse, indeed, has recently been given to the development of advanced technologies like mini- and even micro-thrusters[2, 3]. On the side of space exploratory missions, very ambitious goals require more advanced propulsion systems as well. A rising interest about the study of planets (like Mars or Venus) or asteroids and comets by means of sample and return missions, can be underlined. On the commercial side the development of the modern space economy and also more "traditional" sectors like satellite field cannot be ignored. In fact, all the most important industrial companies (OHB, Rafael, Thales-Alenia Space, Boeing, LSS, etc.) are investing into the development of all-electric satellite platforms, pointing at the progressive substitution of the chemical thruster[8-12]. Several scenarios have been elaborated and they converge into that way and, for example, CNES has recently announced that this kind of reconversion could affect about 50% of the telecommunication satellite market in the next future[13].

Furthermore, the agenda of all the most important international agencies include EP in the list major key-factors for future space mission development. NASA is traditionally heading this field by promoting the cooperation with high-profile laboratories like PEPL (Plasmadynamics & Electric Propulsion Laboratory - University of Michigan) and AFRL (Air Force Research Laboratory) while on the European side, HiPER Program (High-Power Electric propulsion: Roadmap for the future), has been launched by European Union to fund the activities on the next family of electric propulsion based spacecrafts[14]. ESA leads the program and coordinates the consortium, composed of six national space agencies (ASI, BELSPO, CDTI, CNES, DLR and UKSA) as well as some European associations, like Eurospace and SME4SPACE. The objective is to consolidate and improve the competitiveness of the European Space Sector in the field of in-space electrical propulsion.

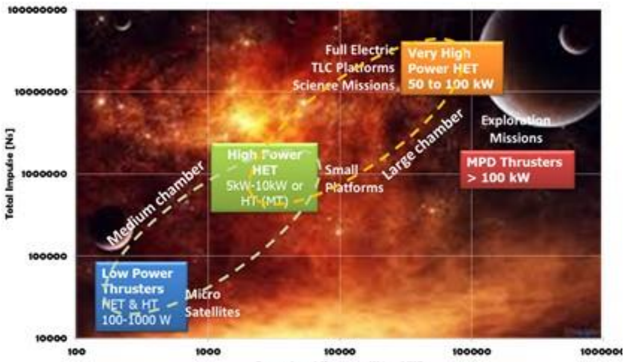


Figure 1. Power range of application for HET and MPD thrusters.

According to Figure 1 three large families (and consequently reference test facility) can be identified according to the power level and mission requirements in terms of total impulse. In other words, from the technological point of view, EP panorama in the short/medium term scenario will be probably focused on the maturation of existing low power EP systems, with power range of about 5-10 kW. According to this view, HET family seems to represent one of the most promising technology as different industrial actors have pointed out. For example, Aerojet has underlined that the launch mass and total power of operational GEO spacecrafts, equipped with EP based on this technology[15], has grown by four times in last 15 years. Also on the very low power application side (mini- and micro-satellites), HET technology is suitable as pointed out by Rafael and Sitael[8, 9, 16]. Other concepts, like SEP, are still under development based on the impulse given by NASA. In the framework of future exploratory missions and introduction of full-electric platforms, the need for high power solutions (up to 100 kW) is arising, as also pointed out by Figure 1. On the long-term scenario side, dominated by high power EP systems, the enabling of the following missions can be foreseen:

- Cargo missions between LEO (Low Earth Orbit) and HEO (High Earth Orbit) for the on-station deployment of satellites (for example also in GEO) or for supporting Lunar and Martian exploration[17];
- Transfers to Near Earth Objects (NEO) or Mars;
- Solar System exploration (moons of Jupiter – for example, Prometheus Project[18]);
- Asteroid missions, manned or robot-aided[19]
- Re-boost of Space Station in LEO;
- Drag make-up in LEO or transfer to high energy;
- Integration for kick-stage in space transportation systems[20,21] – for example, VEGA or Ariane class launchers.

Finally, very long-terms scenarios could include the possibility to develop un-manned and even manned vehicles, equipped with EP, to reach for the planets near to the Earth, as proposed by ESA. Moreover, the coupling with powerful electric generator, even nuclear-energy based, could be launched in order to extend mission ranges beyond the solar system[7].

Given this background and perspectives, the improvement of specific infrastructures, dedicated to extended test campaigns, represents a crucial point both for low or high thrust solution development. Their availability will strongly help the study of the involved basic physical phenomena, supporting the development of theoretical, numerical and design procedures, required to optimize thrusters and components, and also investigate the interaction between propulsion systems and spacecrafts. As briefly aforementioned, this issue is well known by scientific and institutional players, as also underlined by the programmatic points of EPIC Program[22]. In fact, one of the most important parts is represented by the improvement of the European capabilities in terms of test facilities (including advanced diagnostics) and standardized experimental methodologies in order to support the R&D projects and reduce the impact of acceptance and qualification phases. On the research side, appropriate facilities are needed to support the comprehension of the most critical physical aspects and the development of theoretical and numerical modelling, by characterizing the thrusters in terms of performances, plume and long-endurance capabilities[23-26].

III. CIRA Electric propulsion research program

The strategic plan of CIRA has confirmed the efforts in improving competences and know-how in the field of aerospace propulsion in terms of testing infrastructures, design and manufacturing capabilities. These efforts are devoted to support the Italian aerospace companies and cooperate with international institutions, universities, research centers and companies by taking advantage of the significant heritage, consolidated by participating to several national and international projects concerning solid, liquid and also electric propulsion[27,28].

For these reasons, CIRA has elaborated a detailed development plan, based on the realization of state-of-the-art facilities, dedicated to Electric Propulsion. They are characterized by adequate sizes and equipment to enable the tests of the brand new electric thruster and implement R&D activities, starting from HET technology. The brand-new infrastructures have been conceived, to: integrate and even complete the capabilities of present vacuum chambers, already working in Italy but oriented towards commercial applications; make possible the access to a world-class space simulator, suitable for the challenges imposed by the next future high power EP systems.

The program, launched in the second half of 2015, has been named IMP-EP. It includes three principal lines[29], as depicted by Figure 2, and they are devoted to a specific issue as pointed out as follows:

- **line 1** – testing facilities (including their design and realization and the improvement of test competences);
- **line 2** – diagnostics (featuring the development and improvement of basic and advanced diagnostics methodologies);
- **line 3** – test articles (promoting the development of design methodologies and technologies for electrical thrusters, including the set-up of a preliminary design tool, improvement of numerical modeling and post-test analyses and laboratory models manufacturing).

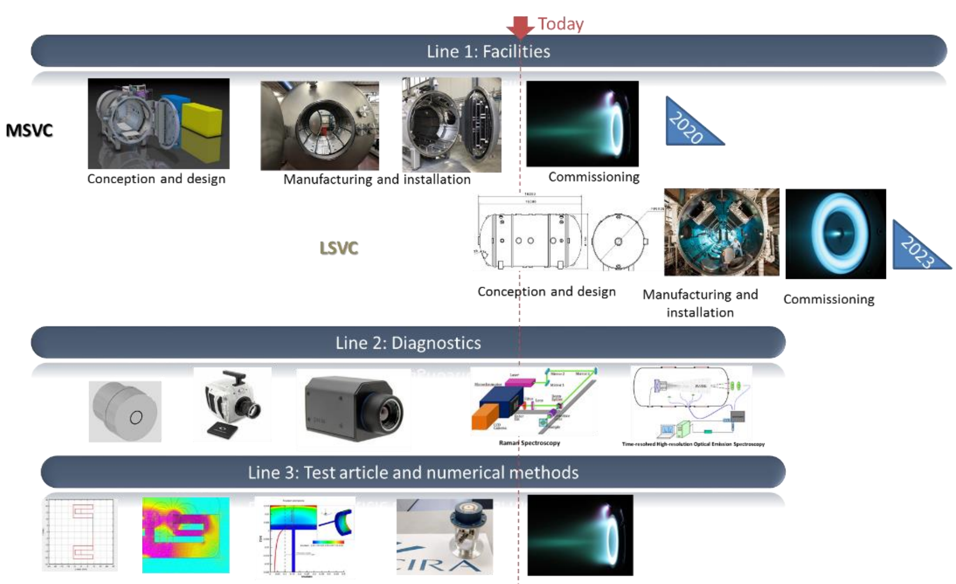


Figure 2. CIRA IMP-EP organization and roadmap.

IV. Implementation and relevant achievements

A. Facility design, installation and preliminary testing

MSVC facility, as conceived and designed, represents a flexible and performing R&D-oriented simulator ready to improve analysis, theoretical and numerical modeling, design and manufacturing competences in the field of EP thrusters with a particular interest in HETs, which represent the core of the initial CIRA efforts. Moreover, it is intended to support investigations on alternative propellants (like Argon, Krypton, etc.) .with respect to the reference one, such as Xenon or innovative ones (like condensable propellants). Future activities regarding other promising technologies, like Helicon and MPD thrusters, have been taken into account to respond to the precise increasing demand for EPS test benches.

Significant achievements have been accomplished on MSVC facility realization, completed at the end of July 2019. The preliminary design has been conducted in house and accomplished in April 2016 while for the final design and realization stage Angelantoni Test Technologies (Massa Martana, Italy) company was contracted. The final design was completed in May 2017 and from November 2017 the manufacturing phase has started at ATT Massa Martana premises; this phase has been accomplished in June 2018 with the preliminary functional tests. Then, the facility has passed the factory acceptance tests and delivered to CIRA premises. The installation started at the beginning of April 2019 and has been completed in July 2019. In the next September the start-up phase will be implemented.

The driving design specifications have been directly derived from the requirements for a reliable electric thruster characterization, endurance and acceptance testing. They can be easily summarized in limiting the interactions between the thruster and the surrounding environment, specifically including mechanical and electromagnetic aspects. The dimensions of the chamber, length and diameter, are of course the primary design characteristics to be defined to allow the free expansion of the beam keeping the point of particles impingement as far as possible from the thruster[26]. This usually ensures also adequate distances between the thruster and the walls to obtain limited distortions of the applied electric and magnetic fields and a low contamination rate due to back-sputtering. The selected dimensions are the following: an overall diameter of 2.0 m (1.9 internal) and a length of about 4.5 m have been chosen. MSVC facility consists of a single body vacuum chamber, made of AISI 304L stainless steel and all the chamber walls have been refined by means of micro-peening process to obtain an appropriate surface finishing, as required by test specifications. The chamber is able to accomplish performance and plume characterization tests and long endurance experimental activities on thrusters, characterized by a power level up to 5 kW.

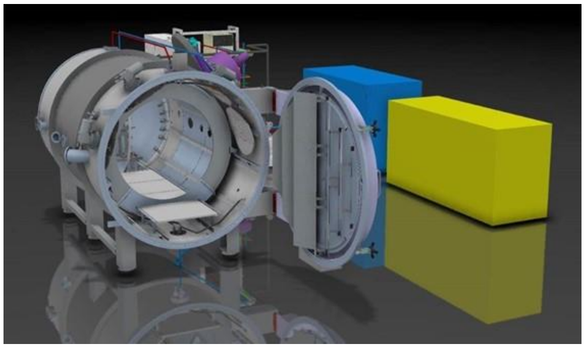


Figure 3. Sketch of MSVC simulator in the preliminary design phase.

The access to the simulator is available from both the end caps: the thrust stand (maximum load of 20 kg) is located near the front-cap (700 mm away from it), being provided with a DN900 flange to ease final operations on the test article; the other end-cap allows for a full access to the chamber by means of a full size door, provided with two hand-wheels and safety micro-switch devices. This solution enables the use of a thrust stand, mounted on a dedicated sled and it will be very useful in case of a complex set-up. In fact, a complete test set-up (including engine, diagnostics, measurement instrumentation and the thrust balance) can be fully configured outside the simulator, then inserted from the end-cap side and moved toward the front-cap by means of specific guide rails. Furthermore, the axial and vertical position of the thrust stand can be adjusted if necessary. Specific pillars, anchored to the bottom of the chamber, allow for the temporary fastening of walkable stainless steel panels (max load of 200 kg), useful in the operation and also in maintenance activities. The machine is equipped with adjustable anti-vibration feet ensuring a longer life of the equipment.

The facility is able to reach ultra-high vacuum conditions, taking advantage of a multistage pumping system, composed of an oil-free primary pumping system (up to $1x10^{-2}$ mbar) and a secondary pumping one. The former (Oerlikon Leybold LEYVAC LV140 and ROOTS WAU 501) consists of a dry pump (100 m^3 /hr) and a root pump (500 m^3/hr), while the latter is composed by a turbo-molecular pump (Oerlikon Leybold TURBOVAC MAG 700 - 700 l/s on N_2) and a cryogenic pump (Oerlikon Leybold COOLVAC 10000 - 10000 l/s on N_2), mounted on the vessel. The ultra-high vacuum condition is achieved by four single-stage cold heads (CHD), which start to work at $5x10^{-5}$ mbar. These cryo-generators are equipped with Oerlikon Leybold Coolpower 250 MD devices and custom pumping surfaces (about 0.60 m of diameter) made of dedicated aluminium plates, working at a minimum temperature of 25 K and guarantying an overall pumping speed of 74,000 l/s on Xe. Each head is connected to a helium compressor (Oerlikon Leybold Coolpower 6000H) and is equipped with dedicated temperature probes and heater devices. Such system is able to reach an ultimate pressure of $5x10^{-8}$ mbar and an operating pressure of $4x10^{-5}$ mbar (at a mass flow rate of Xenon equal to 15 mg/s), respectively while the final overall leak rate will be less than $1x10^{-5}$ mbar l/s in He, as proved during functional tests, recently held. All the accessories servicing the pumping systems are located in a specific skid, as depicted by Figure 4, behind the electronics cabinet. Venting can be accomplished manually by a dedicated valve or by electric valves; both the valves are connected to GN_2 feeding line.

MSVC is also equipped with a series of environmental monitoring devices consisting of four chamber pressure transducers (including Pirani, Penning and full range sensors), one mass spectrometer Residual Gas Analyser (INFICON Transpector RGA MPS-200), dedicated pumping system pressure transducers located on the turbo and cryo-pumps and temperature sensors (type-K thermocouples and PT100 thermo-resistances) serving cold heads and test article.

Figure 4. View of the MSVC simulator during the installation phase.

The chamber is provided by a modular refrigeration system (designed to remove up to 5 kW), consisting into three independent sections, covering the cylindrical section and end-cap one and the plume expansion zone, by means of an annular shroud. Moreover, a specific lining of walls by means of graphite-based solutions has been adopted in order to: manage the thermal load, released by the plume on the chamber walls by impingement; to prevent the warming up of the cryo-surfaces. The baseline evolving fluid is water but the refrigeration system is equipped also with cryogenic valves and pipes in order to switch to liquid nitrogen without any further modifications.

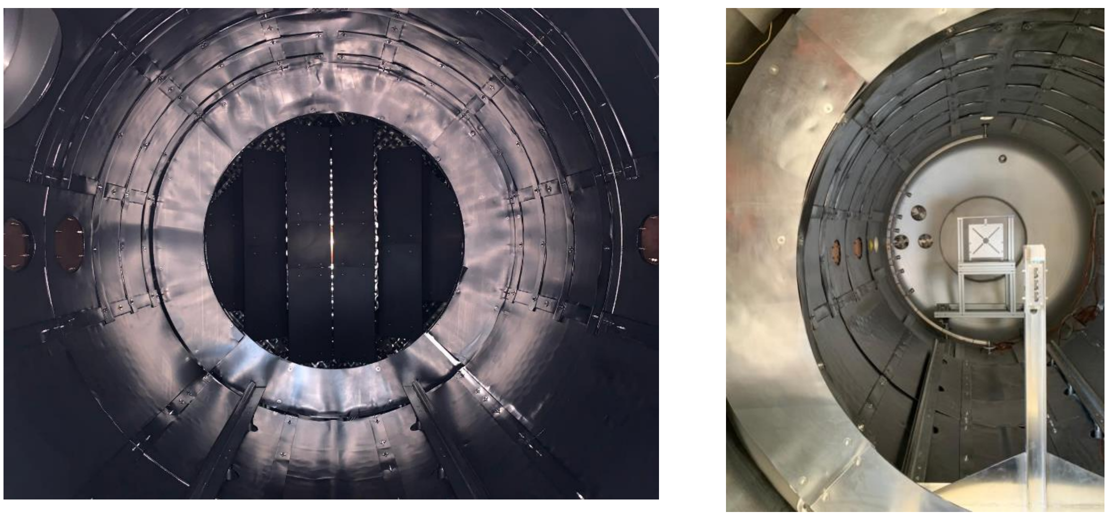
On the back-side, a graphite target has been mounted to shield the chamber from thruster contamination, due to back-sputtering. MSVC has thirty-four feedthroughs overall, including also measurement instrumentations, vacuum generation systems, etc., to ensure flexibility of operation. The electrical and fluidic supply is provided by means of feedthroughs located on the front-cap side as well as the accesses dedicated to measurement data acquisition from the engine. Thus, the facility is provided with several D-SUB, MHV and BNC connectors on specific electrical feedthrough (MDC or PLUG-IN companies). Two propellant flow meters (MKS Instruments) have been installed in order to manage different ranges of mass flow rates (up to 20 sccm and up to 200 sccm, respectively).

The electrical feeding of thrusters and cathodes will be provided by programmable power suppliers (MagnaPower products), selected to accurately control the anodic voltage, (eventually) magnetic circuit, cathode heater and keeper. Four inspection viewports and six optical ones have been realized. In particular, one triplet is located in correspondence with the outlet channel of the engine and includes Fused Silica UV GRADE and ZnSe optics, according to the requirements given by the advanced diagnostics techniques, selected by CIRA personnel (see specific

B section). In the central part of the cylindrical section (at 2000 mm from the front-cap), two 45° oriented optical feedthroughs have been placed in order to point at the center of the test article acceleration channel. Moreover, on the end-cap an additional optics, including a specific protective system, has been mounted. For what concerns the advanced diagnostics, three fiber feedthroughs have been considered in the central part of the chamber and near the thrust stand. Finally, specific feedthroughs have been conceived in order to allow a 1-axis rotating rake working. This rake is dedicated to the intrusive diagnostics (up to 7 sensible elements) and allows an accuracy of 0.5° in angle position and is connected directly to the facility control system.

The facility is equipped with a flexible and efficient control system, able to manage all the operation phases in automatic or manual mode, acquire all the facility and test article operation parameters, guarantee the interface with the test article control system. Moreover, the continuous and safe operation of the facility is ensured by a specific UPS, working in synergy with an electrical generator (located outside as the specific chiller, servicing all the facility subsystems) in order to prevent possible power supply long discontinuity events and preserve long testing operations. At this moment, also an ISO 8 soft-wall clean room (overall dimension equal to 3m x 3m x 3m) has been acquired to support the pre-test, assembly and integration activities, linked to MSVC operation.

The installation in CIRA started on April 2019 and ended on July 2019 (see Figure 4). In the following significant images from the installation phase are reported. In particular, Figure 5 shows internal shroud graphite lining, the diagnostic rake provided with Faraday cups and thrust stand. Figure 6 depicts the lateral view of the simulator where are visible the cryogenic pump, the turbo-molecular pump and two cold heads, optical accesses and pressure sensors, the figure also show the rack for the thruster power supply composed by four different power supply units, one for the anode, two for the cathode (heater and keeper), one for the magnetic circuit.



a) b)

Figure 5. Internal views of MSVC simulator: a) back end-cap, including beam target; b) front cap, including the thrust stand and diagnostic rake.

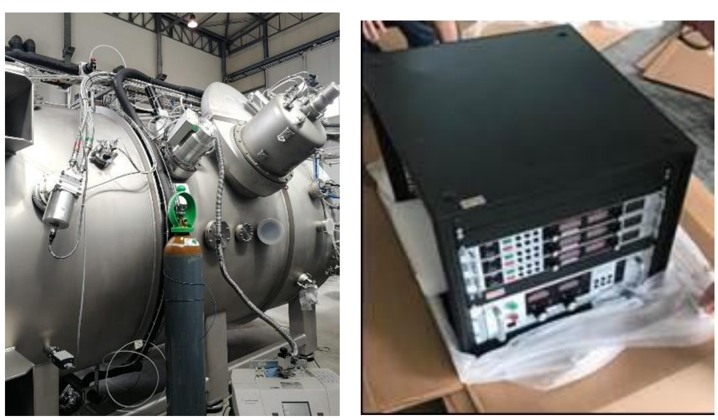


Figure 6. Lateral view of the simulator (on the left) and laboratory power supply rack (on the right).

After the installation some performance tests at subsystem level have been accomplished and, then final dynamic pumping tests have been carried out. In particular, in order to verify the pumping requirements of the facility, xenon mass flow rate values from 1 to 15 mg/s have been considered to be injected into the facility and the pressure measured has been recorder by a full range pressure sensor (Leybold PTR 90N). Results, reported in Figure 7, are in line with the expected design specifications.

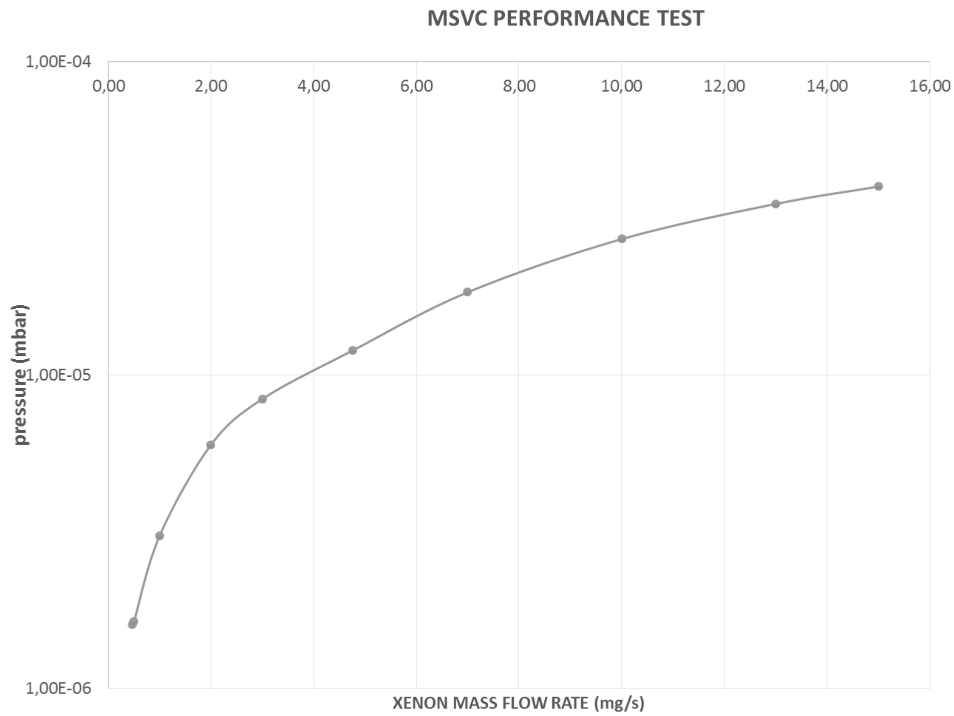


Figure 7. Results of Xenon injection tests in terms of measured background pressure.

On the LSVC design phase, all the requirements including general infrastructures, simulator and support equipment have been already defined. In January 2018 the procedures for the assignment of preliminary design has started. The preliminary design will be completed by the end of 2019. A technical description regarding this facility can be found in Ref. 30.

B. Diagnostics

In the framework of diagnostics line, the use of both conventional diagnostics and advanced ones has been considered, taking advantage of the know-how acquired by CIRA personnel in related fields. The collected information will be important to support the numerical methodologies development and testing capabilities. As aforementioned, the characterization of plasma beam will be accomplished by adopting intrusive diagnostics, in particular, both Langmuir probes - to determine the electron temperature, electron density, and electric potential of a plasma - and nude Faraday probes, used to determine the local ion charge flux of the thruster plume. This equipment has been realized with the support of Grado Zero Espace S.r.l. and consists of an array of 7 Faraday probes with a guard ring and an array of 3 single telescopic Langmuir probes[31]. The acquisition electronics has been realized with a source meter unit, including a power supply, and various I/O cards and circuits.

The Faraday probes[32], pointing at the center of the thruster exit plane, are installed on a semi-circular motorized rake with a mean radius of 885 mm. Each Faraday probe has, respectively, a collector made in pure molybdenum with diameter of 10 mm, a guard ring made in stainless steel with external diameter of 40 mm, and a gap between the collector and the guard ring of 0.75 mm.

The Langmuir probes are installed on a structure, made in stainless steel and movable with respect to the exit plane of the thruster. Each Langmuir probe consists of an electrode in pure tungsten and has a diameter of 0.4 mm and exposed length of 10 mm, and a telescopic shaft of 2 coaxial tubes made in pure alumina. It is ongoing, the procurement of a thrust stand capable to measure thrust from 0 to 100 mN.

Figure 8. Intrusive diagnostics, equipping MSVC: a) Langmuir probe; b) Faraday probe.

At the present time a High Speed Imaging (HSI) and thermography devices have been acquired. HSI allows to globally visualize the HET flow field, without perturbing its operation, and identify the spoke regions characterized by low and high frequency oscillations, affecting the engine. The implementation of HSI set-up, applied to a HET, will be ensured by mean of Phantom® v1212 CMOS camera, as shown in Figure 9a. Thermography techniques include the use of commercial cameras, working in the MIR (Medium Infra-Red) and FIR (Far Infra-Red) ranges in order to evaluate the temperature maps of hardware[34, 35]. Temperature measurements are not intrusive and allow for: a) the estimations of the heat load from the thruster body to the thruster gimbal/mount; b) obtaining information on magnetic circuit heating (avoiding the Curie temperature exceeding) and coil insulation; c) providing data about the thruster functionality and suggest potential methods to improve the efficiency; d) studying the sputtering phenomena of acceleration channel materials , influencing the engine lifetime, with the temperature variation[36]. The hardware is FLIR® A65 and is shown below.

a) b)

Figure 9. **Diagnostics equipment: a) Phantom® v1212 CMOS Camera, Vision Research; b) FLIR A65 thermal imaging camera.**

CIRA is also evaluating the acquisition of non-intrusive diagnostics[33].

a. Doppler Laser Induced Fluorescence (D-LIF);
b. Optical Emission Spectroscopy (OES).

Radiations emitted in the UV, VIS and NIR range by chemical species included in the plasma beam will be studied by means of OES technique. In particular, in the case of HETs, this technique allows time-resolved monitoring of the plume contamination caused by the erosion of the acceleration channel walls. A possible scheme of an optical set-up for the application of OES to a HET characterization is shown by[37]. The technique of Doppler-Laser Induced Fluorescence (D-LIF) can provide non-intrusive measurements of velocity for atomic species and ions, even in the engine channel region and not only in the plume. An example of a possible optical set-up is shown in Figure 10[38].

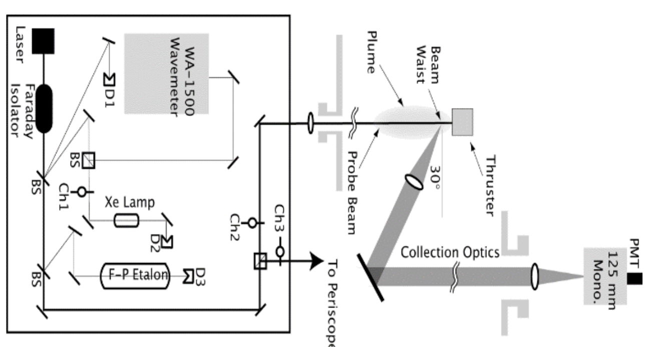


Figure 10. Example of a scheme for a D-LIF set-up[38].

C. Test Articles Development and Numerical Activities

The main goal of the "test articles" line consists into provide test articles for implementing the first experimental activities in MSVC and LSVC facilities, respectively. The development phase of the test article enabled CIRA to use and develop design capabilities of electric propulsion devices and become familiar with the most common problems related the electric propulsion such us, magnetic design and analyses, rarefied gas dynamics, plasma modelling and thermal analyses. Moreover thrusters will follow a technology development phase, considering different mock-up models to be produced and verified at different levels. In fact, they will be tested under leak, vibration and magnetic field point of view before the firing tests[39].

The size of engines and operation have been tailored on MSVC and LSVC testing performances. Thus, it has been decided to design a low power class thruster (hundreds of W) and a high power class thruster (tens of kW), inserted in the reference power level of each facility.

The architecture of the thruster, considered in this first phase, is the Hall Effect thrusters, taking advantage of the scalability and interest shown by the scientific community[40-42]. In fact, HETs are very efficient and competitive electric propulsion devices for satellite applications and are currently in use in a number of telecommunications and government spacecrafts. Moreover, Hall thrusters provide the best thrust-to-power ratio among the EP systems, allowing reasonable trip times and significant mass and cost savings compared to typical chemical thrusters.
Given this background, the first thruster that has been developed is a low power thruster, characterized by a nominal power of 250 W. It is based on HET technology and has been designed according to the criteria reported in Ref. 41. It will be tested in MSVC facility. The thruster, named CRHET-250, is equipped with AlNiCo permanent magnets to generate the magnetic field. Thruster expected performances are reported in Table 1.

This design focuses on the main characteristics of an HET: channel dimensions, magnetic circuit, and anode. Many iterations of the design, obtained with the methodologies described in [41,42] were conceived in order to take into account low power thruster issues as low efficiency and thermal management. This process began with the assumption that the thruster would achieve a target discharge power of 250 W and be capable of being operated within the MSVC testing facility.

Table 1. CRHET-250 expected performances.

CRHET-250	
Nominal Discharge Power	250 W
Nominal Thrust	11 mN
Specific Impulse	1250 s
Thruster Mass	0.45 kg

Figure 11. CRHET-250 3D model.

The anode was designed to provide a uniform gas distribution and, thus, discharge within the channel. Two methods for analysing gas flows have been considered, such as the continuum approach and rarefied flow modelling. The continuum approach treats the fluid as a whole and disregards intermolecular interactions. Rarefied flow modelling is the study of gas flow at near vacuum and takes molecular interactions into account. Typically, a rarefied flow model should be used to determine the flow from the anode to a vacuum; however, due to the present scope, the required knowledge and the computational power involved with performing a rarefied study, the continuum approach was preliminarily used as an approximation for the anode design by using the slip condition approximation. Flow simulation of the anode design was performed in ANSYS® Fluent[43]. Then, Fluent simulations have been cross checked at anode exit with the DS2G code[44].

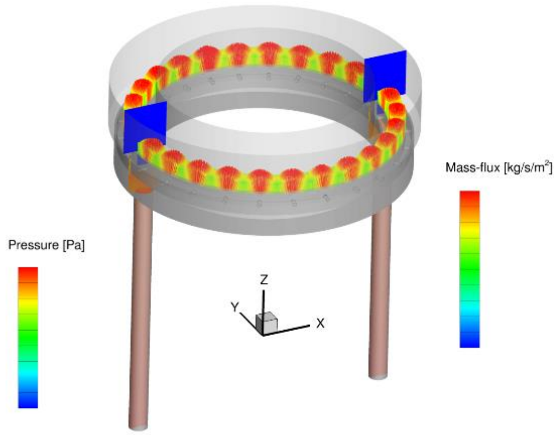
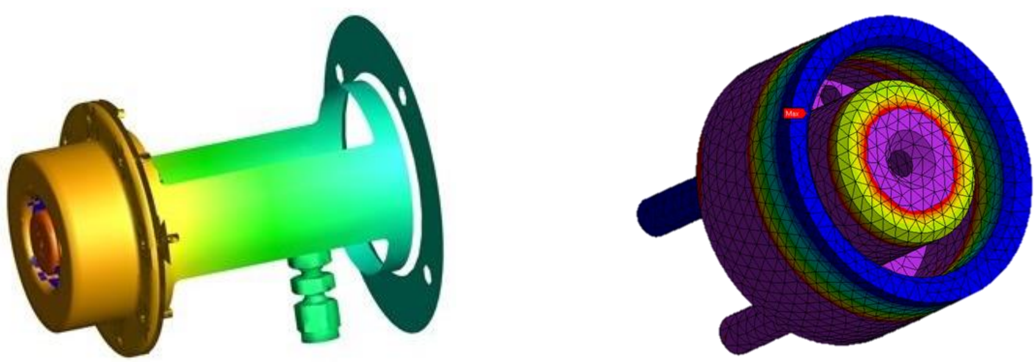


Figure 12. CRHET-250 anode simulation results in terms of pressure and mass flux distribution

Thermo-mechanical analyses on the final configuration have been performed in order to verify: that the magnetic circuit does not reach temperature values that compromise the permanent magnets and consequently the radial magnetic field in the ionization/acceleration zone; the capability of the thruster to radiate externally the heat power; the stresses and the deformation of each subcomponent.



a) b)

Figure 13. Temperature contours obtained by thermal analyses (a) and tensile strength distribution over the BN part (b).

All major components were machined by means of turning and milling processes. No special equipment was needed; only tooling had to be purchased to drill exceptionally small holes, machine tough material, and ream holes for tight tolerances. Most components were cleaned in an ultrasonic bath and dried just before final assembly. The BN channel has been worked with great care and attention was taken during the machining process to prevent oil and dust contamination. The magnets were adapted to the design in order to make them easy to install and remove. The anode is made up of two parts joined by means of vacuum brazing. All anode components were machined from 316 stainless steel. The brazing alloy does not contains materials, resulting problematic for the operation in a vacuum chamber. The gas feed was made up of several Swagelok components. Starting from the vacuum chamber feedthrough side, the feed system consists of a flexible tubing, a dielectric break, a straight tube section with two electrical connections for the anode, and a tube adapter. Then, the gaseous propellant is split into two gas tubes using a T-joint. The first unit has been delivered to CIRA in October 2018 after performing the acceptance tests on anodic part in a vacuum environment, while the other two units have been received in July 2019. Thruster units have been recently outgassed in the MSVC facility and before testing magnetic field verifications will be performed. For this low-power thruster, a commercial electron source has been acquired by Heat Wave Lab and in the early stage of testing, the thruster will be coupled with this cathode.

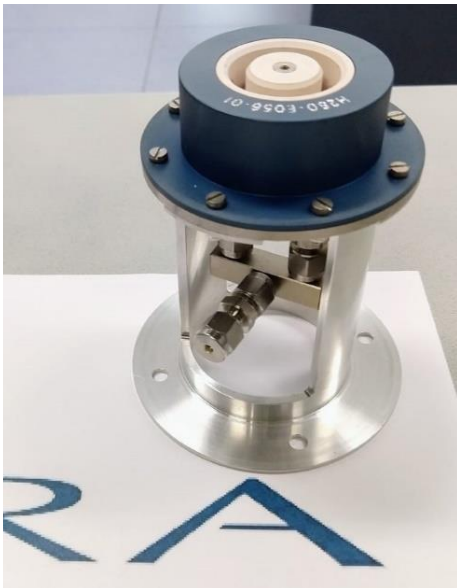


Figure 14. Unit 1 of CRHET-250 assembled.

Moreover a customized hollow cathode has been designed according to the models developed by CIRA[46]. Afterwards it will be tested with the brand-new designed cathode. At this moment, the component is in the manufacturing phase. Its operational parameters are reported in Table 2. Cathode has been verified, in particular, from a thermo-mechanical point of view and simulations have been performed in order to verify the thermal behaviour for the warm-up, the heater on mode (Figure 15) and heater off phases.

Table 2. Cathode basic operational parameters.

Parameter	Unit	Value
Discharge Current	[A]	1
Mass flow rate	[mg/s]	0.097
Discharge Voltage	[V]	14.2

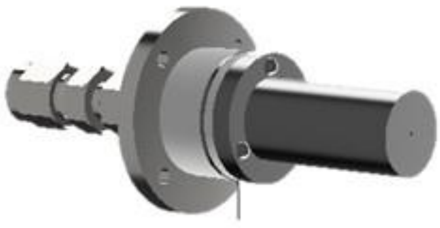


Figure 15. CIRA hollow cathode 3D model.

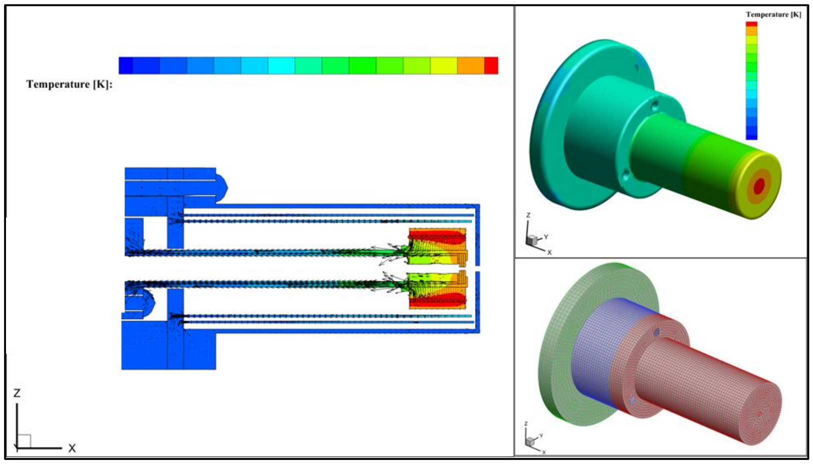


Figure 16. Temperature contours from cathode thermal analysis.

To improve the comprehension of main physical phenomena, involved in electric propulsion, in the frame of the test article line, two numerical models are in development. The first one is related to cathode, and, in particular, a preliminary design tool for orificed hollow cathodes has been developed. Two physical models are included in the tool: a plasma model and a thermal model. A time-independent, volume-averaged model has been developed to determine plasma properties in the emitter and orifice regions. A Lumped Element Thermal Model has been also developed to compute the temperature distributions and the respective gradients within the main elements of the cathode. Details can be found in[46]. Moreover, the development of a code that evaluates the characteristics of the plasma inside a Stationary Plasma Thruster (SPT) is ongoing. The code uses a hybrid-PIC approach (Figure 17), since it allows, without an excessive computational cost, to obtain a precise characterization of the velocity distribution of heavy species, in particular the ions. This feature is extremely important because, among other things, it enables the possibility to characterize precisely the erosion within a SPT, hence to predict the operative life of these devices.

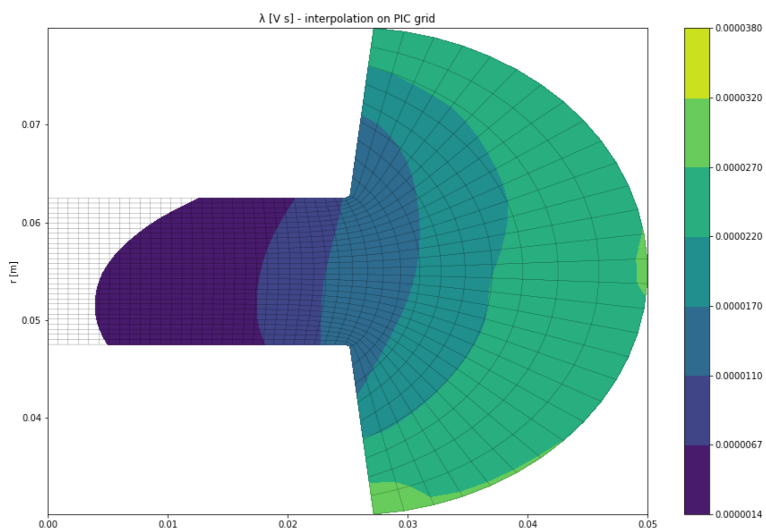


Figure 17. CIRA PIC-Fluid hybrid code: contour plot of the magnetic stream function λ.

V. Conclusion

Electric propulsion is already well consolidated for the use in the aerospace industry but the interest on this kind of technology is still arising, due to its benefits, related to the obtainable high specific impulse (and consequent fuel savings and reduction in mass), multiple ignitions, thrust modulation, re-usability and capability to be adopted in long-running-time missions). Given this background, CIRA, under the commitment of ASI, has launched a specific program on Electric Propulsion, named IMP-EP. Two research-oriented facilities has been included in the plan: the MSVC facility for low power class (up to 5 kW power) and the LSVC for the next future high power class engines (> 25 kW power). The recent advancements of the electric propulsion research program IMP-EP have been presented. In particular, design and manufacturing as well as installation activities of the MSVC laboratory have been discussed, with also the advancements on the research activities related to the design, methodology and diagnostics sides. The program goals are going to be completed by the end of 2019 when first experimental activities are foreseen.

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