HPH.com FINAL REPORT

1 Final publishable summary report

1.1 An executive summary

Aim of this development project was to establish a new propulsion technology in the European market able to open new scenarios, like those covered by mini satellite applications and low cost and commercial missions.

The starting point was a smart concept, the Helicon Plasma source, to be proved and developed in order to achieve the engineering demonstration of the conceptual performances. This challenging program aimed at developing the necessary tools, instrumentation and facilities to design, develop and testing the helicon plasma thruster.
HPH.com research program had the following objectives: (i) to deeply increase understanding and simulation capability of helicon type devices, (ii) to design and develop an helicon propulsion system in the low power regime (50 W), (iii) to identify if this plasma propulsion system can be also used in combination with conventional chemical propulsion systems to increase their performance, (iv) to verify the possibility of installing a helicon plasma source onboard a mini satellite, in order to enable a low-cost demonstration mission, (v) to identify those mission scenarios, which will take benefit from this technology.

The physics and technology investigation had lead to a very good understanding on the involved physical phenomena and also to the development of sophisticated and advanced numerical tools able to simulate the detailed physical processes and providing understanding on a wide family of plasma-based devices. In this frame a set of advanced simulation codes have been established. These codes are not limited to the specific issues of this program, but are a powerful tool for the design and development of many different type of plasma/charged-particle based systems (i.e electric propulsion system, plasma source, ion beam, particle accelerators).

The challenge of dealing with very low power, combined with the necessity of operating with very high power efficiency drove to the development of a completely new technology, called S-Helicon, which is still based on helicon principle, but which introduces complete new features allowing very high performance also in the very low power regime. The S-Helicon provides better operations respect to the RF generator, easier tuning with no need of matching networks, and also higher plasma resistance thanks to high electric field.

This technology has shown a wide range of applicability in many different fields both for research (e.g. particle accelerator) and industrial applications (e.g. plasma treatment, focused ion beam). Particularly it has been already applied in the area of material processing showing the possibility of replacing Chemical Vapour Deposition (CVD) treatments, based on toxic and dangerous gases, with green clean-gas-based plasma- treatment, allowing also a power reduction of about 50%.

A thruster mock-up in the 50 W regime, has been designed, manufactured and tested with different experimental set-up's, in three different test facilities: CISAS, ONERA and KhAI. The test results, which have been achieved up to date, are in line with the design prediction, but need to be consolidated by further testing, as normal practise for a fully new technology development. What has been achieved so far encourages the pursuing of the consolidation phase, allowing the achievement of a maturity level supported by a flight qualification process.

In order to demonstrate the applicability to a low cost mission, and to verify the possibility of low-cost demonstration strategy, a micro-satellite able to accommodate onboard a Helicon Plasma Thruster, has been design and a mock-up built and tested. The study showed that a satellite of 15 kg class is a suitable mean for testing in orbit thrusters of 50-100 W class in order to perform a low-cost In Orbit Demonstration procedure, applying the following mission profile: T= 1.0 mN; Total firing Time = 140 hr; Max Firing Duration = 2 hr.

A combined unit, plasma, chemical propellant have been studied, and the feasibility study shows that plasmas can be effectively used to increase versatility of standard chemical systems, when highly reacting chemicals are considered.

The investigation on a wide range of mission scenarios, coupled with the HPH.com features, showed that the S-helicon plasma system can satisfy classic mission concepts and newly defined mission applications as well, like those related to mini, micro satellites, giving: (i) manoeuvre capability, currently not available on most of mini satellites, (ii) throttling capability allowing for a reduction on the number of engines to be mounted onboard, (iii) possibility of using residuals of chemical rockets, providing a good option for end-of-life satellite disposal. Moreover, the S-helicon versatility can be exploited for air breathing mission concepts, enabling long life low-orbit operations, like those to be planned for debris removal and for emerging wide range operations like in-space refuelling.

1.2 Project context and objectives

1.2.1 Project context

HPH.com research program aims at the development of a new type of plasma thrusters in the range of power lower than 50 W based on helicon-radiofrequency technology. The power regime has been chosen because of the lack of propulsion unit in that regime. However, it should be stretched that this technology is well scalable to higher power operation as already demonstrated by several experiments in the USA.

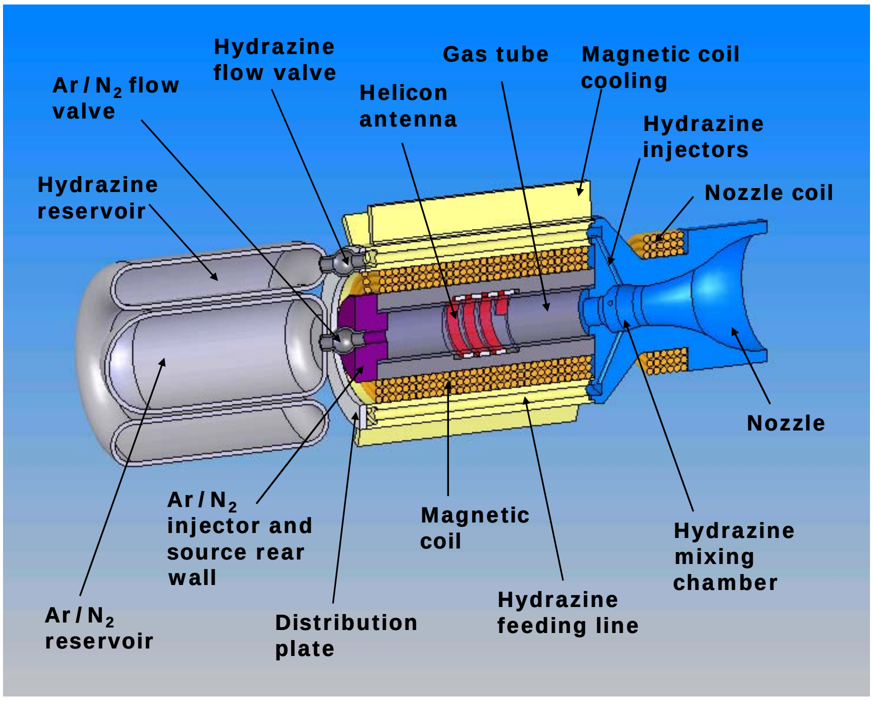


Fig. 1 Sketch of HPH.com thruster

The propulsion system under investigation in the HPH.com research project combines two systems:

- a helicon based plasma thruster which is used stand-alone for accurate low-thrust high-specific impulse operations
- a conventional mono-propellant chemical propulsion system to be used when high-thrust is required. To be applied in combination with the plasma system to avoid use of catalyser.

Helicon based plasma thruster

The basic components of the thrusters are:

- A feeding system providing the required neutral gas flow
- A dielectric tube where plasma is contained
- A Radio frequency antenna wrapped around the dielectric tube
- A magnetic assembly to confine plasmas, optimize power coupling with plasmas and optimize plasmas acceleration into vacuum
- A Radio frequency generator

The helicon source is used as the main element of the thruster. The thrust is obtained exhausting the plasma into vacuum driving it through a suitable magnetic field whose gradient is optimized to increase plasma velocity.

The plasma acceleration mechanisms are the following

1) Thermal expansion into vacuum. This process is the natural expansion of plasmas into vacuum through ambipolar diffusion. Thermal electrons lighter and at higher temperature than ions escape quickly from the bulk increasing plasma potential respect to the outer space. Ions are than driven out of the thruster through this potential. Higher the potential higher is the plasma acceleration. The potential is related to electron temperature and non –Maxwellian electrons. The higher is the electron temperature the higher is the potential. Small fraction of non-Maxwellian electrons can strongly increase the plasma potential and thus the following plasma acceleration. Double layer formation in the plume is related to the natural expansion of electrons with tail. Double layer change the acceleration profile not the overall plasma acceleration. Double layer may influence focusing.

2) Plasma expansion through a magnetic nozzle. Plasma naturally accelerates through a magnetic nozzle thanks to conservation of the adiabatic invariant. Slow diverging magnetic field drive plasma acceleration.

3) Ion heating. This process need to be confirmed but, very high ion velocity have been observed both in the High Power Helicon Experiment and in HPH.com experiment when the feeding frequency is around the lower hybrid plasma frequency, and one of the possible explanation is that plasmas have been directly heated by the Electromagnetic field. This mechanism should increase strongly plasma acceleration.

Main expected advantage of helicon technology respect to current propulsion systems

Helicon technology main features, which may lead to an important improvement in the propulsion scenarios, are:

1) Expected very long operative life: helicon thrusters don't rely on critical component sensitive to erosion as grids and cathodes.

2) Suitability to many different gas propellants: Helicon systems can operate in principle with many different types of gases also reactive.

3) Simple PPU: PPU has only to manage RF power not high voltage operation as in Hall and Ion systems.

4) Throttability: a helicon thruster is in principle a throttable system thus allowing a big range of operations.
5) High power density: a helicon system scale very well with power. The bigger helicon based system developed at Washington University had an ionization chamber of 50 mm in diameter for a 50 kW power

Hydrazine–plasma thrusters

Catalytic-mono-propellant-hydrazine thruster is applied to many spacecrafts as monopropellant propulsion system. Frequently, the lifetime and reliability of the thruster are limited by the degradation of catalyst. For example, particulates of catalyst cause failure of thruster by jamming injector orifices. In addition, such characteristics make the ground validation testing difficult. In this study, we propose to make interacting plasma discharge with hydrazine flow on the thruster nozzle. It is has been verified experimentally (at Tokyo Metropolitan Institute of Technology where a pulsed and a stationary AV discharge was applied) that the activity of discharge plasma is high enough to induce various chemical reactions,
As a matter of fact discharge Plasma not only initiates, but also sustains decomposition of hydrazine.

The current thruster technology scenario shows arc jet thrusters, using hydrazine as propellant, to increase the thruster specific impulse up to about 600 s (instead of the nominal 230 s), providing a thrust in the sub-N range with a specific power of about 10W/man.
Having from one side a plasma thruster, providing thrust in the microN range, allows exploiting the plasma energy to increase the hydrazine thruster section specific impulse up to that of the arcjet, without any specific power increase.

A combined thruster approach will allow for:

- One thruster, two thrust range. Micro-N and Sub-N range, thus capability to perform fine attitude control and house keeping/orbit maintenance with one system only.
- System simplicity: high synergy between the two propellant feeding
- No extra power
- Thruster flexibility: easily to be actuated in pulsed and continuous mode, both ranges, by cross acting the two modes

In the combined plasma thruster hereafter proposed, the hydrazine will be channelled through orifices on the magnetic coil cooler system (to warm-up before interaction with plasma), and then injected into a nozzle cavity at the exit of the plasma source. The hot gas will be than exhausted into vacuum. The magnetic coil placed on the nozzle plays two important roles: a) control of the magnetic field divergence to optimize plasma acceleration during plasma-mode operations, b) control of the cross section of the plasma source before interaction with hydrazine during combined-mode operation.

HPH .com target performance	
Power	***50 W***
Thrust	***1.5 mN ****
Isp	***>1200 S ****

Main aspect in the HPH.com research program

The following table summarizes the main ideas beyond HPH.com project

The main ideas beyond HPH.com project	
To study optimize and build a new thruster concept	Application of the most advanced acceleration principles proposed worldwide. Combination of plasma technology to hydrazine technology in order to develop a unique multipurpose versatile propulsion system Achievement of cost reduction and reliability enhancement due to the intrinsic simplicity of the system
To develop a new versatile and scalable (to higher and lower power) propulsion technology	Helicon thruster is a class of propulsion system allowing for wide saleability (from W to MW). A deep knowledge on this technology allows for the development of an entire family of propulsion system.
To proof small thruster technology can be successfully validated onboard mini-satellite	It will allow for a consistent cost reduction on equipment qualification
To increase knowledge on helicon plasma source	Helicon source are a very efficient mean to generate plasmas thus: It could be applied to different propulsion concept It can be applied on industrial process (in the US is already applied on WAFER production)
Null the gap between EU and the United States	US and Japan at the moment are much more advanced in this field

Science and technology objectives

The objects of the proposal are summarized in the following table and explained in the following text

The main objectives	
Objective	Description
1) Highly integrated codes	Development of specifically created code to analyze and design plasma thrusters combining wave propagation and absorption with plasma evolution.
2) Development of highly instrumented experimental set-up	Development of very versatile experimental set-up equipped full of sensors
3) To design and test a plasma thruster	▪ Application of plasma code to thruster development
4) To design a booster section of the thruster	▪ The plasma hydrazine interaction process will be deeply analyzed The COMBIned thruster preliminary designed
5) To proof that a mini satellite demonstration mission is feasible	▪ Detailed analysis of mini satellite critical equipment

In the following objectives are explained more into details

1) To set-up and develop suitable code able to model into details a helicon plasma source. This issue aims to the development of innovative, highly integrated wave-particle code to explore into detail the behaviour of a helicon radio frequency source and to allow source design and optimization for propulsion concept.
2) To develop a ground testing experiment with a full set of instruments for a very detailed characterization of physical aspects within the plasma, to validate codes and to verify the thruster design. The experimental set-up will be divided in two part: a) a thruster-like section, which will be designed to be tested on different vacuum chamber and which will have its own diagnostic to perform plasma characterization within the thruster, b) an environment simulator section which will be a large vacuum chamber expressly developed for space thruster analysis fully instrumented to characterize plasma expansion into vacuum and thruster performance. The experiments will used to validate codes.
3) To design and test a plasma thruster based on helicon technology: The plasma code developed and validated will be used to design a plasma thruster based on helicon-radio-frequency technology suitable to fly on a mini-satellite. The thruster will be developed as space-like equipment than experimentally tested. The thruster performance will be verified through ground –experimental testing using the experiment set-up.
4) To analyze and design a booster section of the thruster based on a conventional hydrazine thruster on which the hydrazine is heated by plasmas (directly or by mean of suitable heat exchanger) instead of catalytic bed.
5) To build up mock-ups of most critical mini-satellite-subsystems to proof that this technology can be mounted onboard of a mini satellite to achieve space qualification. A detailed analysis of the following subsystems will be conducted in order to identify subsystem requirements and critical issues: power management and control subsystem, attitude determination subsystem (to provide in-flight measurements of thruster performance), data handling and management subsystem (to acquire all diagnostics of the thruster, store and transfer the data), thruster control electronics, structure (including thermal, grounding and charging issues). Than a detailed design of a minisatellite equipped with the helicon-thruster will be done and a functional mock-up will be built to demonstrate feasibility of the all selected critical issues.
6) To deeply investigate mission scenarios allowed by this new thruster technology, identifying possible mission profile and highlighting the advantages. A detailed ingestion will be conducted in order to identify scaling and throttability options than a study will be conducted in order to identify mission profiles achievable using this new technology.
7) To explore applications to ordinary industries. Helicon source have been widely considered in the frame of industrial plasmas because of their high efficiency. The codes developed within this program can be easily applied to source optimization of a variety of industrial processes. A review of industrial applications will be conducted and fields potentially suitable for helicon plasma source will be identified analyzing the impact in term of competitively.

How the project intend to increase European competiveness

The specific issues of the project, which are intended to increase European competitiveness and to Strengthen European Foundation are listed in the following table:

Relevant issue for Strengthening European Foundation	
Objective	Description
1) New generation of advanced space transportation	▪ HPH.com will be the member of a saleable family (from mN to N's)
2) Reduction of space transportation costs and increase in reliability	▪ HPH.com is very simple thus reliable and cheap.
3) Applicability of existing and emerging space power	▪ This technology is not demanding, it can be combined with a variety of plasma sources
4) Dependency	▪ When acquired the technology and know how will be completely European
5) New space exploration scenarios	▪ This technology has already been considered as a first stage of an Earth-to-Mars low-transfer-time vehicle.

- New generation of advanced space transportation systems: This program aims to develop a new family of space propulsion systems based on the same technology (radio –frequency helicon and hydrazine) just scaled in term of size and power. This family of thrusters will allow to cope (depending on power and size) both with primary and secondary propulsion aspects.
- Reduction of space transportation costs and increase in reliability: The development of a new technology scalable and applicable to propulsion system of different size and power allows a strong reduction on development cost thanks to the common deep knowledge on physical aspects involved. It must be remarked that Helicon thrusters for their specific structure are cheaper than other propulsion systems. Moreover concept simplicity and synergy on developing a wide family of thruster will lead to a high reliability of the propulsion system. Finally this study assessed also the possibility of applying low-cost mini satellite for technology demonstration mission. If succeeded it will open new horizon on space qualification.
- Applicability of existing and emerging space power: The electric propulsion concept requires very low voltage sources, thus it doesn't demand specific power sources allowing combination with all of the power system currently available and under development.
- Dependency: helicon sources have been widely studied in the United States, Helicon thrusters are under development on many research centres within the United States, Japan and Australia. If this technology will demonstrate its potential, the European Union will fill the gap that may determine dependency from other countries or difficulties on competing. This project aims to bring European knowledge up to the current state of the art in this field.
- New space exploration scenarios: Combined helicon hydrazine thruster could allow the development of an efficient throttable, variable ISP thruster. Moreover Helicon source has been proposed as a first stage of powerful engine as VASIMR (Variable Specific Impulse Magneto-plasma-dynamic Rocket studied by NASA expressly designed to transport human being to Mars. Thus this technology open potential new opportunity on space exploration, both itself and combined with other technologies, that could lead to: - very challenging sample return missions, - human exploration of planet, an increase up to 30% of payload on initial mass ratio (this value has been calculated as a result of a study conducted by CISAS under ASI (Italian Space Agency) contract to asses the mission scenarios allowed by a variable specific impulse thruster respect to a fixed specific impulse thruster and is

valid in case of mission requiring complex manoeuvres or fast transfer time.

1.3 A description of the main S&T results/foregrounds

1.3.1 Progress in physical understanding

1.3.1.1 *Plasma wave interaction*

Whether structurally simple a helicon based propulsion system is founded on a very complicate physical behaviour that needs to be understood. The following main issues need to be analyzed and considered during the development of a helicon system:

- Wave propagation within plasmas is strongly coupled with transport of ion electrons and neutrals.
- Within a helicon source for propulsion application neutral density varies strongly from the injector to the end. The fraction of neutrals close to the exit section of the thruster needs to be close to few percent of the ion density.
- Super-thermal electron population provides a strong contribution to thruster performance because they increase the plasma potential, which accelerates ions.
- Power coupling is strongly affected by plasma resistance. Electrical features of the whole system from generator to the antenna need to be modelled.

The last issue becomes very important especially when antenna diameter becomes small (which is important to minimize thruster volume), since antenna inductance become very small and thus comparable with strain elements of the circuits, and plasma resistance is small due to the small volume. This introduce important issues as: (i) very high antenna current (tens of amps magnitude) with related Ohmic dissipation into strain elements and heating, (ii) criticality during coupling due to very high reflected power in case of even small mismatching, (iii) small authority of the matching circuit due to low antenna impedance.

These issues are present also on helicon source for industrial application, but become more critical in the development of a propulsion system because:

- A helicon source for industrial application doesn't need to operate close to 100 % ionization efficiency
- A helicon source for industrial application doesn't need to operate close to 90 % of RF power transfer efficiency.
- Electron temperature and plasma potential normally requested on industrial processes are low in order to do not damage the substrate.
- A propulsion system is very compact (thus low plasma resistance).

These are the main reasons why within the HPH.com research project a huge effort has been put in developing innovative codes able to perform accurate simulations of the overall processes within a helicon discharge.

The main outcome have been:

- Simulation strategies need to be strongly improved including transport.
- Standard helicon theory is not applicable because limits to just simple magnetic field configurations
- Radial and axial neutral gradient and neutral depletion plays fundamental role.
- System approach including in the analysis also the external power circuit need to be performed.

1.3.1.2 *Plasma expansion into vacuum and acceleration*

The RF energy deposited in the electrons is the energy absorbed by the plasma. One part of this energy is spent in ionizing the plasma, a second part is lost as atom radiation, and a third part is lost into the source walls, thereby heating the thruster structure. The rest is kept as plasma internal energy and will be transformed into directed kinetic energy mainly outside the source, in the magnetic nozzle. A subsonic/supersonic transition takes place around the source exit if the maximum magnetic strength (i.e. the throat of the magnetic nozzle) is located there.

A two-dimensional model of the subsonic plasma dynamics inside the source has been derived. The main processes that are taken into account are the following. First, the depletion (through electron-bombardment ionization) of the neutral gas emitted (normally) at the source rear plate. Second, the axial flow of the plasma, both toward the rear plate (where it recombines and adds to the injected gas flow) and toward the tube exit; the backflow constitutes mainly a loss phenomenon, which can be quenched by suitable magnetic screening. Third, the radial plasma confinement, which is very effective, if a near-axial configuration of the magnetic field is adopted. The small radial diffusion of the plasma creates an azimuthal electron current that generates a radial magnetic force that balances the large radial gradient of pressure, like in theta-pinch equilibrium. Ions remain weakly magnetized and do not develop a significant azimuthal drift. A dedicated study has determined the whole radial structure of the plasma and scaling laws for the particle and energy losses into the wall. These losses are negligible for magnetic fields of several hundred Gauss.

Outside the source, the divergent magnetic nozzle channels the current-free plasma beam and accelerates it supersonically. For usual values of the magnetic strength (say 0.5 to 1 kGauss) and medium to heavy propellants (argon, xenon…) electrons are fully magnetized, thus diverging along the magnetic streamtubes, while keeping the azimuthal rotation acquired inside the source (i.e. isorotating). However, ions are weakly magnetized and their large inertia tries to keep them straight. Then, in order to maintain plasma quasineutrality a large radial electric field develops. A consequence of it is an enhanced radial rarefaction of the beam, which is very positive for the nozzle performance, since it preserves partially the beam collimation. Except around the beam/vacuum edge, ion streamtubes separate from the electron/magnetic streamtubes. This separation generates longitudinal electric currents, even if the plasma is current-free. The upstream or downstream closure of these currents remains an open problem.

The 2D model that has been developed has also shown that the thrust gain mechanism in a magnetic nozzle (with no walls) is the reaction magnetic force of the azimuthal plasma current into the magnetic structure (i.e. the coils or permanent magnets) of the thruster. This is just a more elaborate setting of the classical one of two parallel currents attracting each other when running in opposite directions. Here, in order the thrust gain to be positive the plasma current must be diamagnetic, which is just the condition demanded by the theta-pinch equilibrium too. The magnetic thrust in the nozzle adds to the pressure thrust inside the source.

If the plasma density is large enough, the plasma beta (i.e. the thermal-to-magnetic pressure ratio) is not negligible and the diamagnetic plasma current is large enough to cancel partially the applied magnetic field. Inside the source, this reduces the confinement and thus increases the wall losses.
Outside the source, it modifies the magnetic nozzle shape, which becomes more divergent. On the one hand, this reduces the nozzle performance; on the other hand it enhances electron demagnetization downstream that can be positive for detachment. It must be noticed that this scenario is opposed to the magnetic-stretching scenario (caused by paramagnetic plasma currents and leading to thrust losses) claimed by some authors.

The role of plasma resistivity and electron inertia in electron separation from the magnetic nozzle has been studied through a perturbation analysis. It has been demonstrated that resistivity and azimuthal inertia of electrons behave in a similar way: both produce an outwards separation of the electron streamtubes, which seems natural (stating that the plasma tends to expand towards the vacuum) but it is a negative feature for nozzle performance and for the downstream detachment of the plasma beam.

Highly-suprathermal electrons, possibly generated by wave-electron Landau-damping interaction have been detected in helicon sources. There is some experimental evidence and theoretical support for the combined presence of thermal and to lead to the formation of a double layer in the expanding plasma. Therefore, a study has been devoted to the formation and propulsive role of intermediate double layers in the plasma beam of a helicon thruster. It has been shown that the electric potential and density profiles become steeper as the relative density and temperature of hot electrons increase, and there is a parametric region where quasineutrality cannot be maintained and the non-neutral double layer or discontinuity develops. The current-free double layer is always weak in the sense that the relative space-charge is modest. From the fluid dynamic point of view the double layer is the consequence of a highly varying speed of sound, leading to the existence of three sonic points instead of one and two of them cannot be crossed in a regular way. There is no change of plasma momentum across the double layer, just an abrupt transfer from electrons to ions. Thus, the double layer, since it does not include any thrust mechanism, has no propulsive role: it is just a way to diagnose a significant population of hot electrons.

1.3.2 Advanced simulation code

1.3.2.1 *Innovative code to simulate plasma expansion and acceleration*

The semi analytical models of the plasma flow inside the source and in the magnetic nozzle have been the basis for UPM to develop two fluid codes: HELFLU for the source and DIMAGNO for the nozzle.
HELFLU computes the two-dimensional plasma flow inside the source for an axial magnetic field and a given plasma temperature. The two main performance parameters of the code are propellant utilization and current efficiency (or ratio between the plasma mass flow at the source exit and the total mass flow through source boundaries), which is a component of thrust efficiency. The code allows to investigate the performance parameters in terms of source size, magnetic strength, mass flow, and electron temperature (which is related to the absorbed power). The parametric region for near total propellant utilization can be determined.

DIMAGNO code is a 2D code for the plasma expansion in the divergent magnetic nozzle, which solves completely: the 2D maps of plasma discharge variables, such as density, electric potential, velocity fields of ions and electrons; the longitudinal and azimuthal plasma currents; the spatial distribution of the differential thrust and of the plume efficiency. Input parameters are the applied magnetic topology and strength, the plasma conditions at the nozzle throat (such as the Mach number and the radial distribution of plasma density). For high-density beams the code also computes the induced magnetic field and modifies the nozzle shape accordingly. The method of characteristic surfaces is used to integrate the hyperbolic differential equations, so a future development should be able to integrate beyond the nozzle turning point and determine the far downstream behaviour of the plasma.

Finally, the matching of DIMAGNO and HELFLU solutions allows to complete the full simulation of the helicon thruster by determining, first, the relation between the absorbed wave energy and the electron temperature and, second, the thrust efficiency

ONERA NOZMAG . In the frame of the HPH.com project, **ONERA** has developed a numerical tool to simulate the plasma acceleration and expansion in an electrodeless thruster, such as the

Helicon thruster. This tool is based on a fluid model of the plasma. In this model, the plasma is seen as a conductive quasi neutral medium, expanding in a static magnetic field. This model is valid within certain plasma conditions, compatible in what is typically found in helicon discharge.

This simulation tool allows computing the production of plasma in an ionization chamber, and its acceleration and expansion in a magnetic field. The magnetic field can be very simple, as the one produced by a coil, or more complex, as the one obtained with arrangements of permanent magnets. Similarly, the ionization chamber and thruster geometry can be quite simple, such as an open cavity, or more complex, such as a chamber with a nozzle-like shape.

Based on this simulation tool, ONERA has performed an analysis of the plasma expansion and detachment on realistic thruster geometries. For example, the figure below shows on the comparison between the plasma plume observed on the Qualification Model developed by KhAI (left) and the result of a simulation of the thruster (right). The features observed in the plume are also observed in the simulation, in particular the formation of a wall-directed plasma jet on the side of the thrusters, due to the magnetic cusp existing on the permanent magnets used for this experiment.

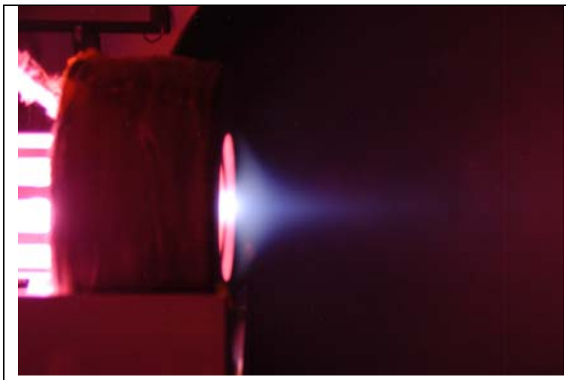


Fig. 2 *View of the plasma plume on the thruster*

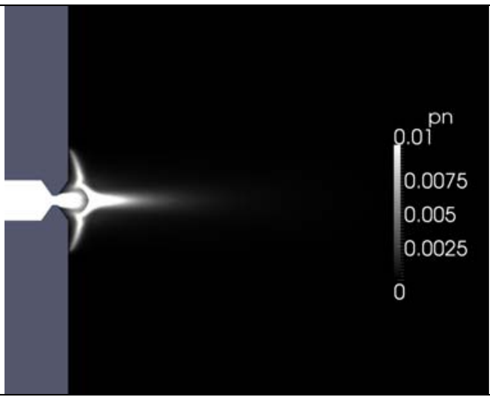


Fig. 3 *View of the simulated plasma plume*

With this simulation tool, a parametric investigation of the thruster performances, in term of thrust and power, has been conducted. Various geometries have been simulated, and the relative contribution of the different thrust-production mechanism (surface pressure, and volume force due to Lorentz forces) has been evaluated. Based on these simulations, potential improvements have been identified, to increase the performances of the thruster.

1.3.2.2 *Innovative plasma simulation tools for modelling and optimization of plasma systems*

Several codes have been developed to simulate the helicon plasma system, which is the core of HPH.com. Within a helicon thruster, the plasma is magnetized in order to enhance the lateral confinement and to allow the propagation of plasma waves (helicon and cyclotronic waves) excited by the radio frequency (RF) antenna. Differently from industrial helicon sources, the plasma-wave coupling is optimized in order to maximize the ionization fraction together with the kinetic energy delivered to ions.
The codes developed in the framework of HPH.com have such general features that they constitute a generalized framework for the treatment of many kinds of plasma sources, with arbitrary geometries, vacuum and plasma conditions. In the present contribution the features of each code are briefly presented.

SPIREs and EQM combined codes: In practical applications, plasma discharges have often a cylindrical shape. The axisymmetry of such devices has allowed the development of two simplified design tools, useful for a rapid evaluation of the discharge properties. The two tools, called SPIREs and EQM, solve two connected problems related to the equilibrium conditions of the plasma discharge. From the iteration of the two codes together, the absolute values of the discharge are calculated.

SPIREs calculates the electromagnetic fields propagating inside the plasma column (plasma-wave coupling problem), by solving the two Maxwell wave equations (the Faraday-Lorentz and Ampere-Maxwell equations) in cylindrical coordinates plus a generalized Ohm's law. The plasma is represented by the classical Stix cold plasma tensor. **EQM** solves the macroscopic transport of plasma and neutral species and the equilibrium of the discharge for a given deposited power. The two codes combined together provide for a give source, excited by a specific antenna and with specific magnetic field: (i) power deposited into plasmas, (ii) radial neutral density, (iii) radial electron density and temperature, (iv) radial ion density.

PartyWave: is a particle-based tool for the analysis of distribution functions of plasma species, especially for the study of electron distribution functions and the possible appearance of hot tails at low pressures. This code allows the evaluation of finite-temperature and wave-particle non-linear effects. The code is an electromagnetic Particle-in-Cell, with a 1D radial solver of Maxwell equations, and a 3D particle mover in cylindrical mesh. This coupled code can evaluate the plasma currents in two different ways: by modeling the plasma as a tensor, or by modeling the plasma using particle discretization. This double method sheds light onto physical phenomena and acts as a detailed design tool at the same time.

F3MPIC: F3MPIC is a three-dimensional plasma Particle-in-Cell code with an unstructured mesh coupled with a 3D FEM electrostatic and electromagnetic solver in time domain and frequency domain.
PIC code feature allows for detailed particle simulation of particle dynamic within the source. Differently from fluid code, takes into account microscopic and local effects.
F3MPIC is a complex code, which is a research program itself due to the great difficulty of developing a 3D Electrostatic/electromagnetic PIC code with unstructured meshes. The result was a highly versatile analysis tool able to manage complex geometries, with an arbitrary number of species, both charged and neutral. The geometry of the simulated device can be easily imported from a generic 3D CAD tool. F3MPIC was developed for the optimization and detailed design of helicon and general-purpose spacecraft thrusters, but it can be adapted for each type of plasma device and for several kind of antenna geometry. The code is also equipped with specific MonteCarlo modules able to simulate collisions between particles of different species

Particle-in-Cell: The code evaluates the particles trajectories of a n-species plasmas with a Boris-Leapfrog scheme under the action of electromagnetic fields generated by the plasma itself and by other external sources. An arbitrary number of charged species can be treated. Both plasma and non-plasma regions can be managed. At each time step, charge and current densities on nodes of the unstructured mesh are obtained by means of appropriate weighting schemes.

Unstructured mesh: An unstructured mesh composed of tetrahedra has been chosen for its larger capability to treat with arbitrary complexity geometries in three dimensions with respect to regular Cartesian cells. Particle tracking locates particles in the mesh, using a fast and simple priority-sorting algorithm. The main effort of the development of F3MPIC was devoted to realize a robust and fast algorithm for tracking each particle inside the unstructured mesh. Several different algorithms for the management of exception case have been implemented to avoid long searching loop. As a result, devices with shapes of arbitrary complexity can be easily treated, as for example imported from a 3D CAD model.

Consistent solutions of electrostatic and electromagnetic fields: Static and dynamic electromagnetic interactions among charged particles are treated consistently. Their electrodynamics is solved at each time step together with the solutions of their fields plus the fields generated by any assumed external source. The electromagnetic problem can be electrostatic, magnetostatic or electromagnetic in nature. The solution of the electromagnetic fields produced by the antenna current and by particle motion is implemented through linking of the particle solver to an electromagnetic finite-element solver.

Boltzmann electrons
In some cases, the full-kinetic treatment of all the plasma species is unneeded, especially in all cases when the ion dynamics is more relevant than electron dynamics. In these cases a Maxwell-Boltzmann treatment of electrons is appropriate. The Boltzmann-electrons formulation has been included in the Poisson electrostatic solver of F3MPIC as an optional tool that can be activated on demand.

Collisions
Interaction of charged particles with neutrals and collisionsF3MPIC can manage also not-charged particles. The collision between charge particles and neutrals involves a MonteCarlo Collision (MCC) tool.

Computational efficiency
A big effort in the development of the code has been put on optimization of linking e efficiency, in order to minimize computational time. In particular, the parallelization of the electromagnetic solver and the building of the solver as a unique program revealed to be key issues during the code development. Moreover special algorithms have been also developed to allow calculation also in the high energy range.

Boundary management
Different types of boundary conditions are implemented, both for particles and for the field solver: particle emitter, neutral injectors, particle exit port, floating and biased conductor and simple dielectric.

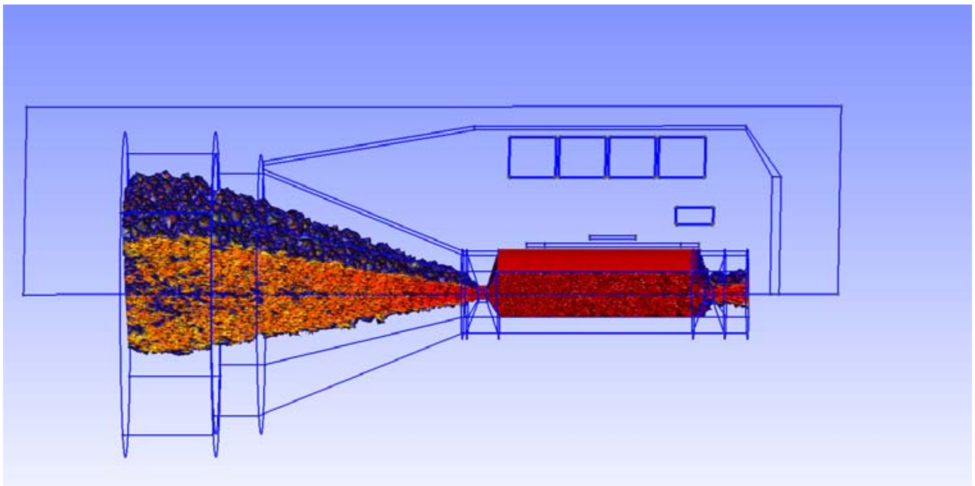


Fig 4 Simulation of HPH.com plasma thruster

F3M PIC is a very versatile tool. It has been already used to simulate the ion extraction process for heavy particle accelerator at the Legnaro National Laboratory in Italy.

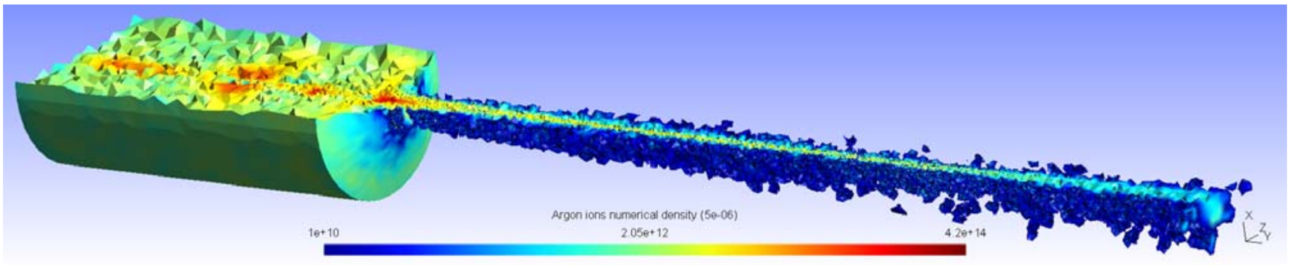


Fig 5 Simulation of FEBIAD source of the LNL laboratory Italy

1.3.3 Experimental set-up of developing and optimizing plasma thrusters

HPH.com has been characterized by a very intense experimental activity in order to clarify physical aspect within the helicon thrusters and to optimize the system up to performances relevant for space applications.

Test have been conducted on three separate laboratory in order to reduce development time and to cross check results:

- University of Padua CISAS (Italy): A development test bed have been set-up allowing test s on a wide range of thrusters configurations
- National Aerospace University "KhAI" (Ukraine): A development test bed have been set-up allowing also thrust measurements
- ONERA (France): a sophisticated test bed has been set-up to allow for performance verification.

1.3.3.1 *Experimental set-up to design and develop helicon plasma thruster*

The experimental facility developed at CISAS is composed by a vacuum system, thruster mock up and diagnostic system and.

Vacuum apparatus.

The hydraulic scheme of the apparatus comprises valves, pressure sensors and pumps.

The vacuum apparatus consists of a 2-m length-0.6-m diameter vacuum chamber and a pumping system of 10000 l/s.

The maximum vacuum level reached without the injection of a mass flow is 1e-7 mbar and the possible presence of contaminants is monitored through a mass spectrometer before each experimental operation. In case of mass flow injection, the vacuum level depends on the mass flow value and the pumping line activated, normally for the mass flow rate used (between 10^{-7} kg/s and $4x10^{-7}$kg/s) is in the range of 10^{-5} – 10^{-4} mbar.

Thruster mock-up

The thruster development model is installed outside the vacuum chamber to allow quick modifications of the experimental set-up. The main components are the following:

1) a *pyrex expansion bell* directly linked to the vacuum chamber, where plasma is ejected; this component allows the observation of the plasma beam;
2) a *pyrex tube (i.e.* the *plasma source)* with a inner diameter of 19mm and an outer diameter of 25mm where the plasma is generated;
3) a set of *ceramic outlet diaphragms* that can be changed in order to test different outlet diameters;
4) a *ceramic injector* with a 2mm central axial hole;
5) an *injection system,* responsible of gas feed into the source; a piston mechanism allows to change the source length; the mass flow is regulated through a MKS feedback controller in the range from 0.1 up to 0.4 mg/s with an accuracy of ±(0.008+0.1% rv) mg/s, where rv stands for reading value;

6) an *antenna* for plasma generation, coaxial to the plasma source, and a RF power supply network able to operate at different frequencies;
7) a *permanent magnets* frame, coaxial to the plasma source and axially movable along the source; a brief description is reported below.

Fig. 6 shows a picture of the overall assembly of the development model and highlights the main components.

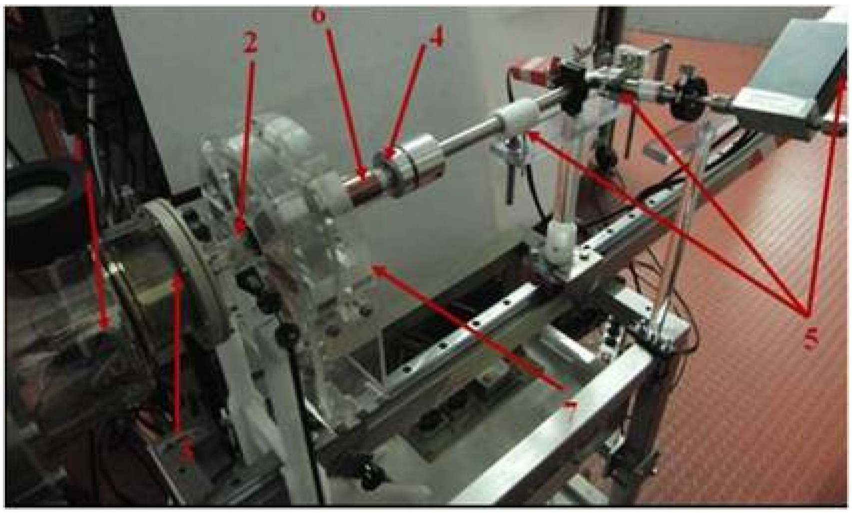


Fig 6 Main components of the thruster development model: 1) pyrex expansion bell; 2) pyrex source (i.e. plasma source); 3) outlet diaphragm; 4) ceramic injector; 5) injection system; 6) antenna; 7) permanent magnets frame.

The experiment can be placed both outside and inside the vacuum chamber.

Diagnostics systems

Optical spectrometry

Two optical spectrometers are used to acquire the emission spectrum of the plasma, in order to extrapolate information on the ratios between atomic excitation and ionization as well as on the electronic temperature.

The coupled employment of these devices allows the observation of a broad band of the emission spectrum from the near UV to the near IR and at the same time to focus on the lower wavelength region where the main ArII lines are present.

Microwave interferometer

The working principle of this instrument lies on the phase difference between a microwave reference signal and a microwave beam, which crosses the plasma; this phase shift is due to the plasma effect on the beam itself.

The phase resolution of the interferometer is equal to 0.06°, leading to a density resolution of 0.5×10^{16} m^{-3}, for a plasma thickness of 20mm of diameter.

Finally, the phase is measured through a low noise digital phase detector with a phase noise of 0.01°. The plasma thickness is estimated by means of a CCD camera.

Fig 7. The microwave interferometer

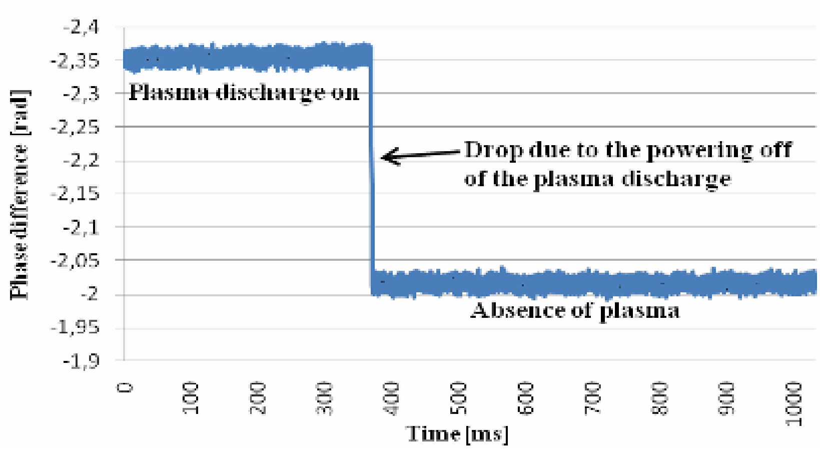


Fig 8. The phase difference drop due to the powering off of the plasma discharge. The value of the drop is a linear function of the plasma density

RPA and Faraday cupnd Langmuir probe

The Retarding Potential Analyzer is used to evaluate the ion distribution function of the plasma beam and to investigate the prospective presence of multiple populations, allowing the comprehension of their influence on thruster performances.
Faraday cups are also used to measure the overall current provided by the thruster.

Both RPA and faraday cups can be moved in front of the plasma beam through a vacuum slit arrangement.

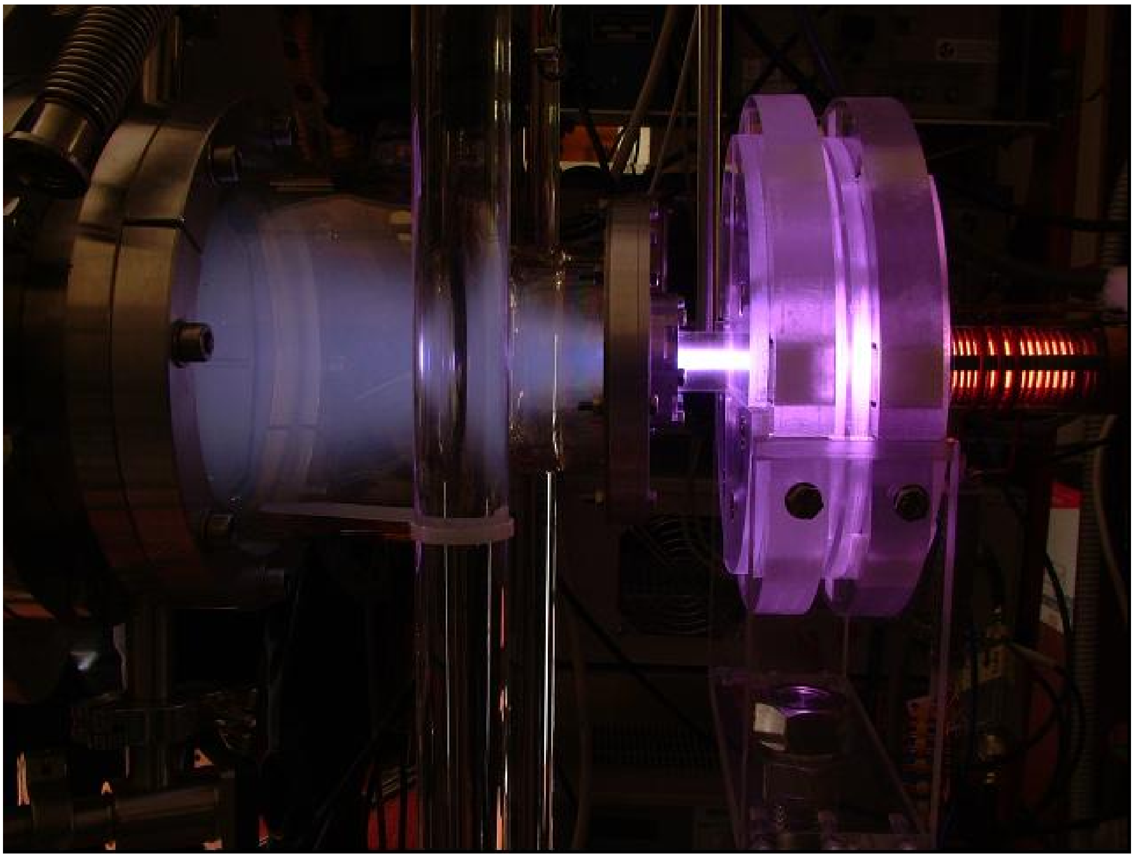


Fig 9. Thruster mock-up at UNIPD-CISAS laboratory.

1.3.3.2 Experimental set-up for thrusters development at KhAI

KhAI electric propulsion department includes full equipment complex, experience and qualification personal for development, manufacturing and testing of electric propulsion thrusters (EPT) and full propulsion systems.

In the department laboratories there are stands for electric propulsion testing, vibration test equipment, vacuum metal and ceramic soldering stands, electron microscope and other technical equipment. KhAI laboratory have been updated to allow full testing of RF based plasma thruster.

Fig 10. EPT testing stand, vacuum soldering stand, electron microscope, EPT testing stand

Measuring equipment includes complex of plasma parameters measuring by single and double Langmuir probes, complex of plasma parameters measuring by multigrid (RPA) probe, spectrometer and pendulum thrust balance. Measuring complexes are equipped by three axis movements systems.

Stand's gas storage and supply systems, mass flow controllers and power supply systems were developed and manufactured at KhAI too.

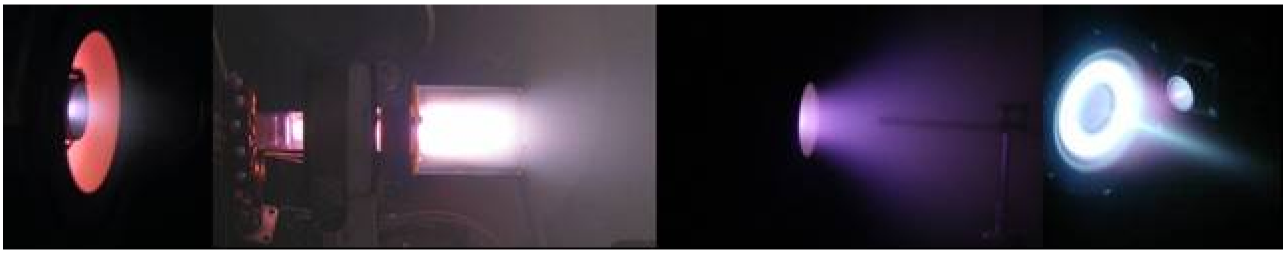


Fig11. Helicon propulsion systems and Hall effect tested at KhAI

1.3.3.3 Experimental set-up for detailed characterization of plasma thruster performances at ONERA

The three helicon thrusters that have been developed in the frame of this project by KhAI (Engineering Model and Qualification Model) and CISAS (Engineering Model) were tested in ONERA vacuum chamber using dedicated experimental setups developed for HPH.com. Thrusters performances are evaluated in terms of typical plasma thruster parameters (ion current density, ion energy distribution, and plasma potential in the beam) and direct thrust measurements with a micro/milli-Newton balance. Specific electrostatic probes (Faraday probe, Emissive probe, Retarding Potential Analyzer) have been designed at ONERA to perform characterization of helicon thrusters.

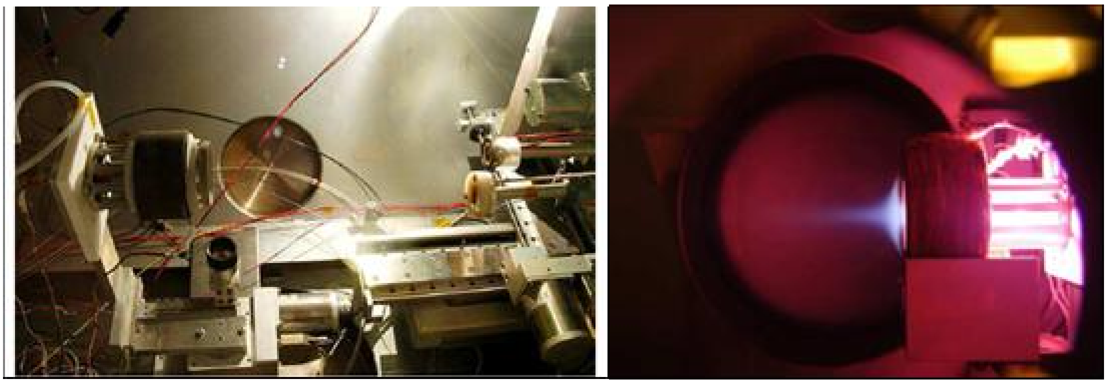


Fig 12. View of Beam Profile Setup with KhAI EM with permanent magnets (left) and PMEA (right).

KhAI Engineering Model has been tested on Beam Profile Setup. The thruster is mounted on a rotation stage in order to scan plasma plume properties with fixed electrostatic probes as a function of beam angle. This setup allows operating the thruster with permanent magnets or with Electrical Analogy of Permanent Magnets (PMEA) whose position can be adjusted, so that the topology of magnetic field can be varied in the helicon source and in the magnetic nozzle.
UPD-CISAS Engineering Model has been studied on Parametric Experiment Setup, which allows moving, with respect to the discharge tube, the different parts of the thrusters (the antenna, the magnet assembly, and the gas injector) in order to optimize helicon source and plasma beam properties. Optical diagnostics have been used to compare radial distribution of light intensity and emission spectra in the helicon source. Moreover, the electrostatic probes have been mounted on a three-axis translation stages system, and axial and radial measurements of plasma plume in the two modes have been performed.

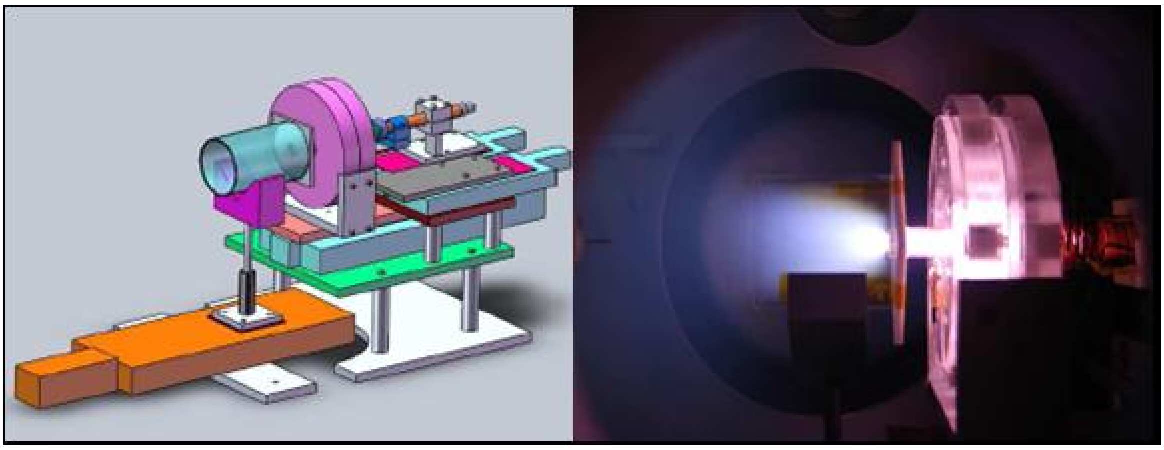


Fig 13. View of Parametric experiment setup and CISAS EM thrusters.

A new thrust balance dedicated to helicon thrusters has been designed and built by ONERA in the frame of this project. This microNewton balance, based on the principle of a pendulum, is especially designed to reduce disturbances from thruster equipments. KhAI Engineering Model was mounted on it for thrust measurements.

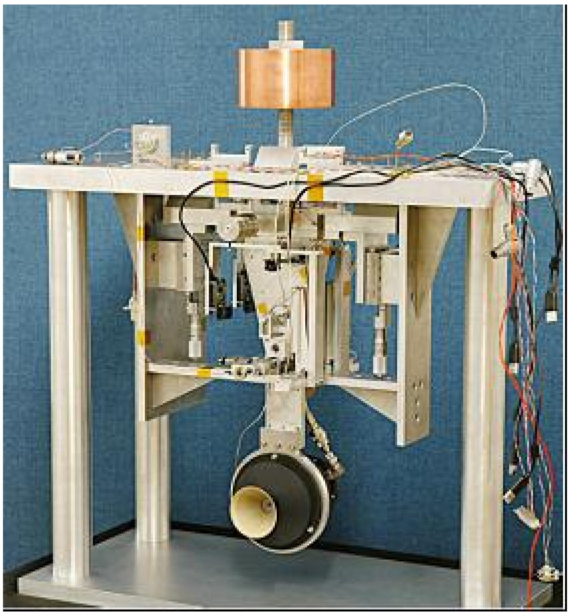


Fig 14. KhAI QM mounted on thrust balance outside the vacuum tank.

1.3.4 Development of innovative plasma thrusters

1.3.4.1 *Innovative concept for plasma generation and acceleration*

At the beginning of HPH.com program several experiments have been conducted to investigate behavior of standard helicon systems applying standard during the HPH.com program, it has been recognize that for space operation helicon source introduced several issues related to power coupling which could potentially limit the range of application and reduce competitively respect to other propulsion systems. For this reason a completely new technology has been developed and tested within this HPH.com program called S-Helicon. The detail of this technology cannot be provided because it is under patenting procedure.

Main feature of this technology are:

1) The matching system to allow power coupling into plasmas is based only on variable frequency generator
2) The S-Helicon drastically reduces power losses in the electrical circuit thanks to very high impedance even in case of very small dimensions.
3) The S-Helicon allow for very high ionization fraction also at very low power.

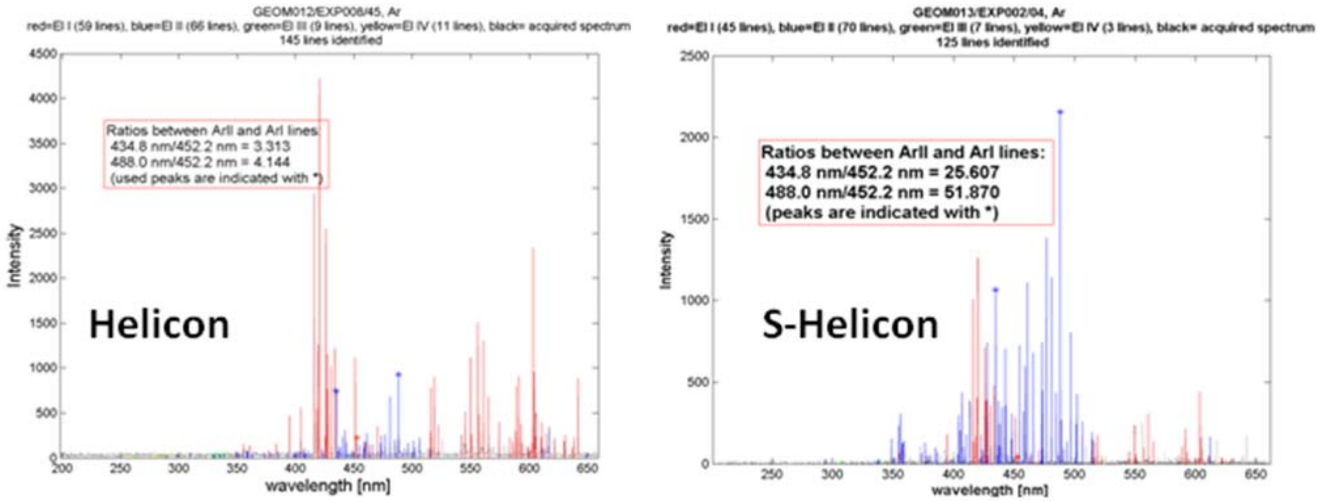


Fig 15 Spectra obtained after optimization procedure at 50W with a m=0 helicon antenna (left) and a S-Helicon (right). Blue lines represent ion lines. Ionization level and temperature achieved with S-Helicon is great by a factor of 3.

1.3.4.2 *The HPH.com plasma thrusters*

In the frame of HPH.com program, beside several laboratory models developed in the three laboratory involved two representative flight model have been developed:

1) EM1 was based on standard helicon technology. Its porpoise was to verify performances of pure helicon technology on a flight representative engine respect to laboratory scale, and especially to acquire data for thermal models and manufacturing processes.
2) QM1 was based on S-Helicon technology and was intended as a performance demonstrator.

Thruster engineering model 1 (EM1)

EM1 manufacturing was the final achievement of several technology optimization steps. The final mass was 420 g; main dimensions are 132 mm x 80 mm (diameter).

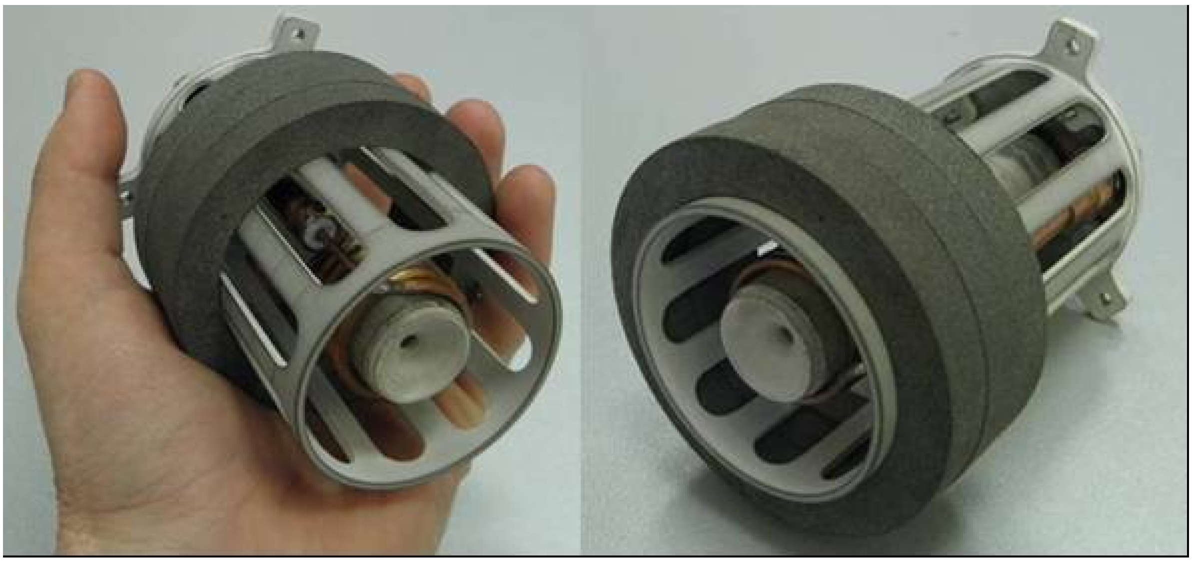


Fig 16 Thruster EM 1

EM1 was experimentally characterized in KhAI as follow:

- Thruster temperature measurements using thermocouples;
- Ion current and IEDF measurements using RPA for different gas flow rate and different magnetic field;
- Ion current and IEDF measurements using RPA for different pressure in vacuum chamber;
- EM thrust measurement by indirect method.

Photos of thruster EM operation are shown on Fig.17.

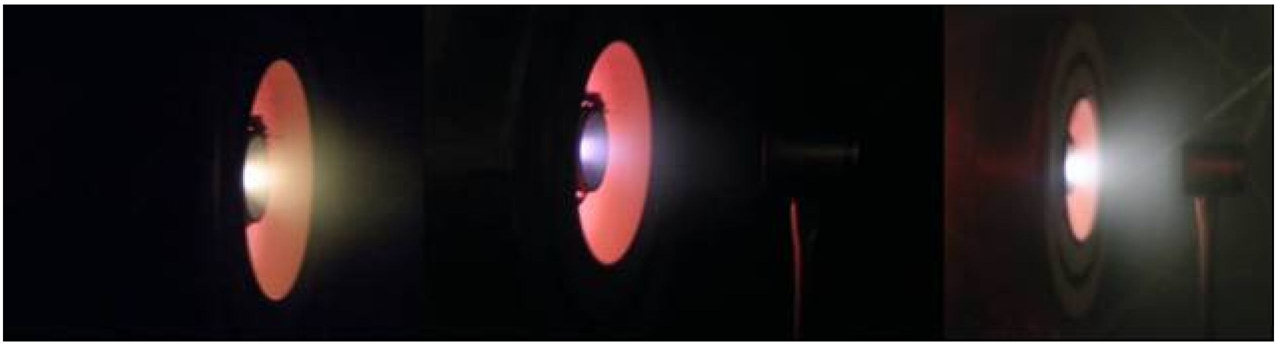


Fig 17 Thruster EM operation

Thruster qualification model (QM)

During the final development phase of the program a new thruster model, specifically designed to demonstrate performances have been design and manufactured.

Manufactured thruster QM is shown on Fig. 18. The thruster was designed and manufactured around the S-Helicon antenna in order to exploit its specific feature. The final mass of the thruster is much higher than before (1990 g) due to the magnetic assembly who affect the total bas as 70%. Lighter mass magnets were not available in a time frame compatible of the project, however, based on new magnet assembly the total mass of the system have been estimated around 1 kg.

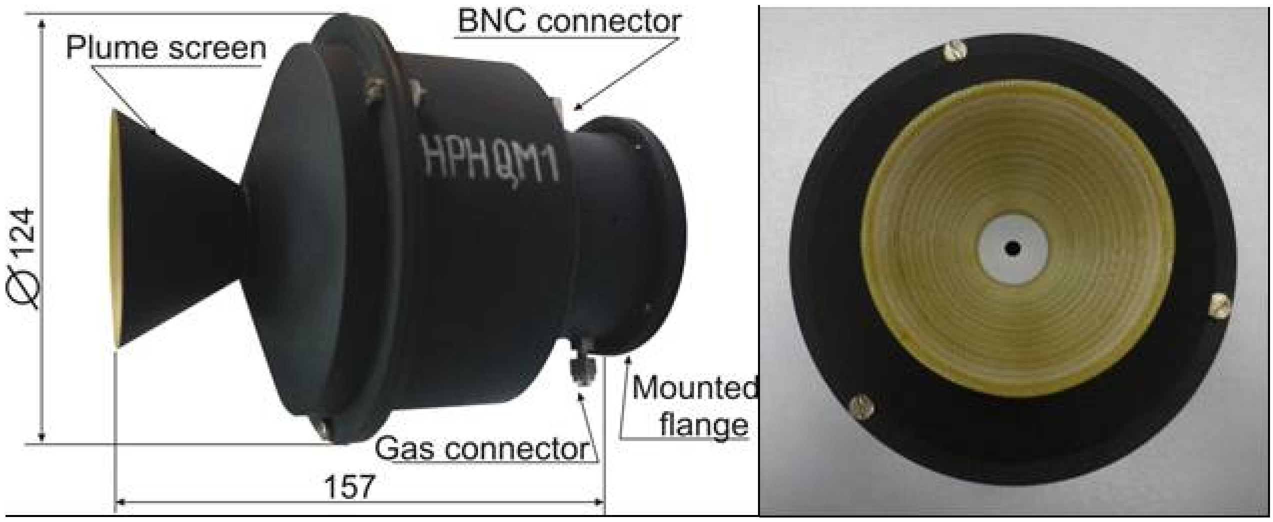


Fig 18 Thruster qualification model

QM1 was manufactured, assembled and tested in KhAI.

Photos of thruster QM operations are shown on Fig. 19.

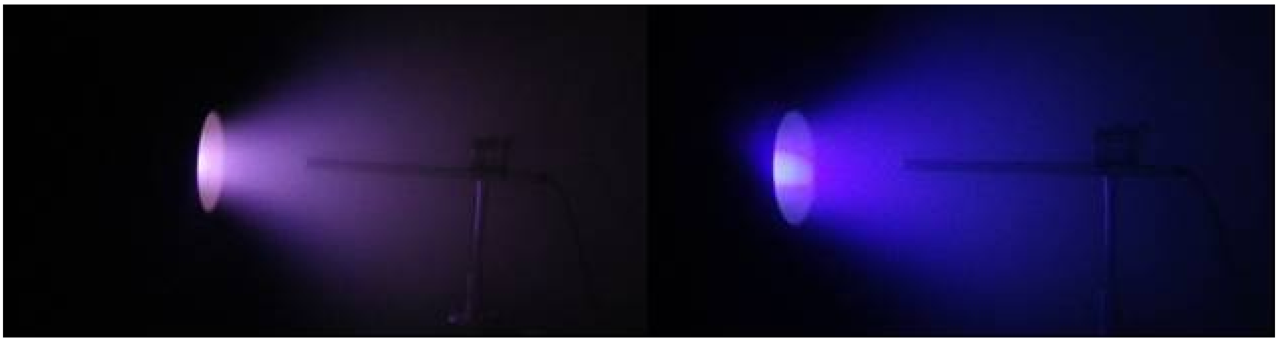


Fig 19 Mass flow rate 0,6 mg/s and 0,12 mg/s

Obtained thruster QM parameters in optimal operating point are:
Mass flow rate - m = 0.12 mg/s; RF power – 8 W
Thrust - F = 0.5 mN; Specific impulse – Is = 422 s; Efficiency – 13 %.

Thrust could not be measured in the higher power regime due to unacceptable errors. Performances in the higher power regime have been estimated through current measurements. Thrust - F 1.4 mN @ 45W (extr.) Specific impulse – Is = 1300 @45W (Extr.)

QM1 have been then transferred to ONERA for further testing. The operational mode, both in terms of operational mass flow rate, and performances couldn't be replaced at ONERA. Whether further analyse are required the investigation conducted identify as possible explanation the different morphology of the vacuum chamber and its interaction with the electric nozzle.

1.3.4.3 *The combined mode HPH.com thrusters*

A feasibility study has been conducted to verify the possible technical solution to decompose secondary-chemical monopropellant using plasmas instead of the catalytic bed. This solution finally leads to indications for the design of a twofold stage thruster having the secondary-chemical propellant stage combined with a plasma stage. The benefit at system level of this solution is the following: the possibility to provide capabilities for fine attitude control, which requires micro N thrust range and will be covered by the plasma-only stage, and housekeeping, which requires sub-N thrust range, covered by the secondary-chemical propellant stage, both during the same mission and onboard the same spacecraft, with the same device.

Two different approaches were followed in this investigation:

- **"heat exchange" approach:** this solution maintains the plasma and secondary-chemical propellant separated up to the discharge nozzle, which is, in principle, a twofold geometry nozzle. In this case the thruster case is made in a way the plasma heat is partly transferred to the external secondary-propellant jacket. The secondary-propellant, flowing through the jacket is heated up and therefore it decomposes and generates a pressure increase that will generate thrust through the discharge nozzle.
- **"direct interaction" approach:** the secondary-chemical propellant is injected in a way that its contact with the plasma generates a sudden decomposition of the propellant and the consequent generation of the extra-thrust. This second approach, for its innovative character, has been the preferred choice and object of a deepest investigation.

Prior to these investigations an accurate choice of the chemical monopropellant to be used was performed, in a view of anticipating the long term international view of adoption of greener propellants respect to those presently commonly used. From the study appeared that the best combination between greenness and easiness of decomposition is the N_2O, while hydrazine still remains the easier one to ignite. The two previous investigation approaches were hence directed toward the exploit of these chemicals.

The **"heat exchange" approach** investigation showed the feasibility to thermally trigger the N_2O decomposition. Three numerical models (a pug-flow reactor model, a nozzle model and a lumped model) were built and integrated together.

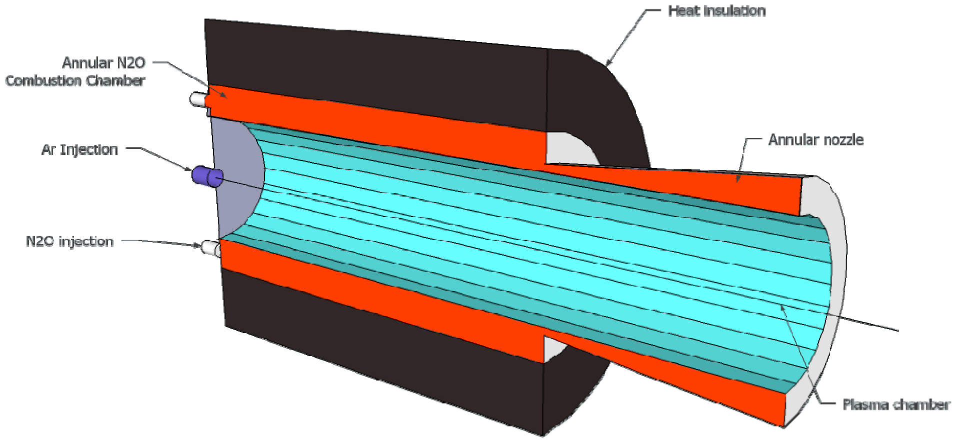


Fig 20 Sketch f the COMBI configuration based on the heat exchange approach

The interesting result of the N_2O ignition theoretical feasibility resulted reduced by manufacturing limitations. To achieve ignition and sustainability combustion chamber conditions the nozzle throat height shall be very small (order of 10 μm), with machining problems and risks of misalignment. In addition, thermal and radiative issues make this solution even less appealing.

The **"direct interaction" approach** investigation was initially performed on Ar/N_2O. Two independent models were built:

- A 1D model which includes transport of the working gas (Ar) as well as the transport of Ar and N_2O ions, and the Boltzmann Relation for the distribution of electrons, which together with Poisson equation determines the distribution of electric field;
- A 0D thermal decomposition model coupled with a plasma discharge model, which includes energy equation for the electron temperature, energy equation for the neutral/ion temperature and continuity equation for each species (electrons, ions, neutrals)

Both the models confirmed the unfeasibility of the N_2O ignition by plasma interaction.

Being hydrazine extremely easy to decompose, a new investigation was performed on this propellant. The 0D model was rewritten from scratch in order to take into account new chemical species and new reactions. The decomposition easiness of hydrazine quickly showed that its ignition with plasma could be feasible even with relatively low power inputs of 100W. In this perspective, in order to properly design an integrated system able to work in plasma model and in chemical mode, different chamber dimensions were simulated.
Simulation results showed the feasibility of obtaining a continuous combustion with the present Qualification Model chamber dimensions, which includes chamber length, diameter, and area ratio between throat diameter and chamber diameter. The final achievable hydrazine mass flow rate is 0.5 g/s. The achievable thrust is within the range of 1.5-2.5N depending on nozzle area ratio and efficiency.

The preliminary design of the Combined thruster, other than combustion issues, had to estimate and consider the thermal behaviour of the device as a whole: combustion gases can exceed 1500-2000K and close to the combustion chamber are located the magnets which Curie point is around 600K.

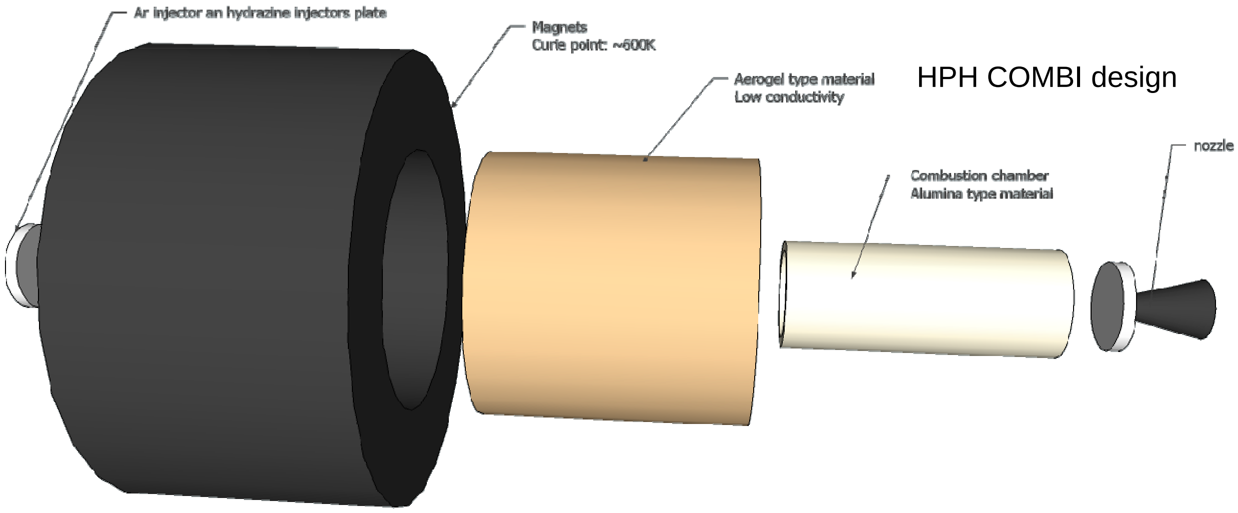


Fig 21 HPH.com COMBI design

The preliminary Combi design foresee an alumina combustion chamber, able to withstand very high temperature, included in a shell of aerogel type material, which has an extremely low thermal conductivity. The heat flux directed from the chamber to the magnets is hence reduced. The final design is able to maintain the magnets initial temperature within a range of 10K variation with a 10s hydrazine shoot.

1.3.5 Design and development of minisatellite for demonstration missions

The objective of the HPH.com WP6 is the design of a microsatellite platform to test in orbit a new type of plasma thruster based on helicon-radiofrequency technology in the range of power up to 50 W. The tests could involve both attitude and position control.

The spacecraft bus designed is lightweight, simple, robust, practical and adaptable for Dnepr launch vehicle. Upon request the satellite can be adapted for almost any launch vehicle.

The structure is modular, easy to assemble and disassemble. It allows change up until the last minute and requires minimal work to gain access to any components.

The microsatellite configuration is a rectangular prism, its dimensions are about 45x50x50 cm as shown in the following figure.

The HPH.com microsatellite is very simple and it consists of 2 aluminum honeycomb decks, 4 side panels and 4 deployable solar panels. Each deck allows boarding a different subsystem. Its simplicity allows to easy manufacture the satellite keeping low the costs. The small size of the microsatellite suggested to enlarge the area dedicated to solar power generation designing deployable solar panels. The following image shows the unfolded satellite configuration.

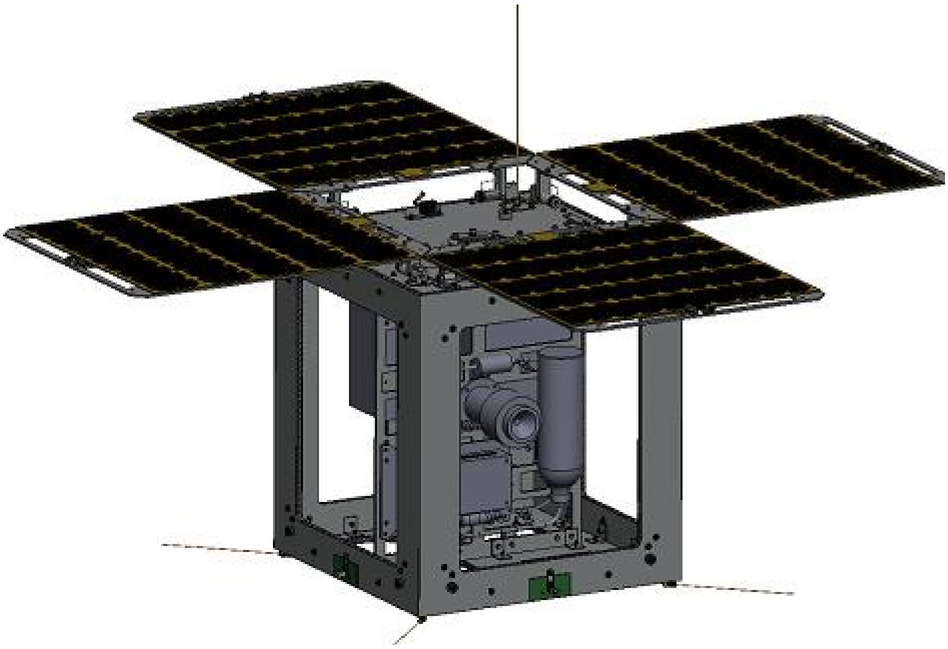


Fig 22 Final Unfolded Configuration

The HPH.com microsatellite power system is in fact based on solar cells and lithium batteries. The special technique developed by GAUSS, Group of Astrodynamics at University of Roma, allows manufacturing solar panels maintaining the manufacturing costs very low. The satellite completely assembled is showed on the following image.

Fig 23 Satellite assembled

The attitude control system is designed to guarantee the orientation of the satellite in order to achieve its mission goals. Desired satellite attitude is specified by the need of simultaneously allowing the orientation of the HPH propulsion system in the desired direction (along satellite's velocity) and of the solar panel surfaces towards the Sun in order to generate the great amount (for a microsatellite) of power required by the propulsion system. Different techniques for attitude control have been analyzed and the final configuration selected is based on magnetic coils, made by GAUSS team, for coarse pointing and desaturation and on commercial reaction wheels for fine pointing.
The satellite attitude during the orbit is showed in the following image.

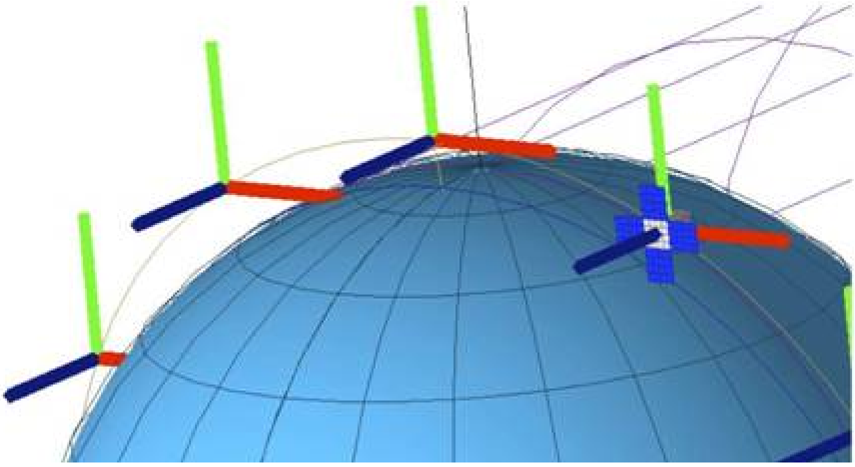


Fig 24 HPH.com microsatellite orientation (blue axis is Z+ in Sun direction)

The orbit determination is crucial to evaluate the HPH performance. For this reason different sensor have been analyzed. Orbit Determination is capable of establish satellite orbit with a precision of some meters, in order to give a precise estimate of the orbital semiaxis increment expected for each propelled phase. Orbit determination will be performed using a GPS receiver as main sensor. Attitude determination is based on a magnetometer, a precision sun sensor and inertial measurement. On board filtering will be implemented for sensor fusion and better accuracy.
The on board computer subsystem is made up of a specifically designed printed circuit board which will host the micro-controller and the other circuits needed for data storage, communication, conversions, timing and execution of the tasks.
Two different on board computer systems have been designed and manufactured by GAUSS team during the project. The first one is based on Rabbit microprocessor, has been replaced by the ABACUS computer based on MSP430 Texas Instrument microprocessor. The on board computer selected has been already tested in orbit during the UniCubeSat-GG mission during the VEGA Maiden Flight.

The scientific data downlink will be allowed exploiting the UHF, VHF and S-Band on-board radio.
Communication architecture is based upon Link Budget evaluation by considering the signal to noise ratio evaluation.
Considering the peculiarity of the HPH.com thruster it was needed to evaluate the compatibility between the thruster and the satellite subsystems. The main systems involved in the compatibility analyses are the thermal control system and the Control and Data Handling (C&DH) system.
The thermal control system is passive and based upon optical characteristics of external satellite surface covering material. The thermal control environment needs to take into account also the heat generated by the HPH.com thruster and its electronics. The simulations and the tests performed suggest that the use of special painting and teflon material is needed to avoid thermal problems during the missions.
One of the main issues to board the HPH.com thruster on a microsatellite is the possible EMC

interference with the main subsystems of the microsatellite. The use of special shielding based on ferrite material allows avoiding this kind of problems. The results of functional tests performed by GAUSS team and CISAS team demonstrate the compatibility between microsatellite subsystems and HPH.com thruster.
The positive results achieved during the thermal vacuum tests and the mechanical tests performed qualify for space the satellite.

1.3.6 Scalability and mission scenarios

1.3.6.1 *Scalability*

The thrusters type allow for good scaling, with a good scaling factor. Conservative calculation shown that the thrusters plasma source scale of a bout a factor of 10 in diameter when power is scaled by a factor o 1000. Moreover this system shows to maintain acceptable efficiency value also at very low power (below 15 W) thus allowing for throttable configurations. More system versatility can also be obtained

1.3.6.2 *New mission for formation flight*

The advent of small satellites has given rise to a new view on space configurations, experiment performance, solution of new fundamental and applied space problems. In particular, it became possible to form a group of satellites, which orbit at some distance from each other and solve a common problem. The main feature of formation flight is autonomous navigation of each satellite and control of the satellites relative position in the group. These configurations can be static and time varying. The ability to determine and control the satellites relative position makes it possible to reconfigure the system, to ensure the execution of manoeuvres, approach and even docking of the satellites. Consider formation flying control algorithms with the HPH.com thruster use under the mission strategy developed within the project.

Relative position control on basis of the impulse solution

Let the mass of satellites be equal to 50kg. Consider a circular relative initial satellites trajectory with radius 500m. Satellites are flying nearby the orbit with inclination 57^0 and altitude 400 km. Assume the desired relative trajectory to be a circle with radius 100m. For such a change of relative trajectory required $\Delta V_h = 0.4$ m/s, $\Delta V_{r_1} = 0.1$ m/s at point $u_0 = 0$ and $\Delta V_{r_1} = -0.1$ m/s at point $u = 180$ degrees. For achieving such ΔV one can switch on thruster at point, for example, $u_1 = -3.5$ degrees with about 220mN of thrust and switch of thruster at point $u_2 = -3.5$ degrees, so, it takes about 100s of thrust work. Then, in such a way one can switch the thruster at in the neighborhood of point $u = 180$ degrees with a thrust about 60 mN also during 100s. The relative trajectory of that example is build. First session of control was executed with certain error caused by continuous impulses. But the second session eliminates this error by couple of thruster switching on. Second control session is applied much smaller thrusts then first because of small orbital elements mismatch. So, in such a way one can maintain relative trajectories of the satellites. In considered example it is reasonable to use during first control session hydrazine mode of thruster hence it requires much less power to produce required thrust then helicon antenna (80W against 3300W). However, small mismatches should be eliminated by helicon antenna because it has bigger specific impulse.

Single-axis formation flying maintenance

Assume the satellite moves in a central Newtonian gravitational field. Consider the differential equations of relative motion in the orbital coordinate frame, known as the Clohessy-Wiltshire equations. These equations are widely used to study the motion of the daughter satellite in the vicinity of the main satellite. The variables x_1, x_2, x_3 describe the along-track, out-of-plane, and radial relative position of the daughter satellite. Assume that we can control the daughter satellite. The respective control force is oriented along the induction vector of the local geomagnetic field. It is proposed the satellite to be equipped with bidirectional thruster installed along the satellite axis of orientation.

1.4 Potential impact

1.4.1 Support to optimization and design of new plasma systems for ordinary and science application

Application to Ion beam technology

In his classical lecture "There's plenty of room at the bottom" done at Caltech in 1959, Richard Feynman anticipated the idea of using focused electron and ion beams to obtain better microscopes. After more than 60 years, Focused Electron Beams (FEB) represents the core of worldwide-spread scanning electron microscopes (SEM), and together with FIB represent practical tools in many laboratories and industries, with applications extending even beyond Feyman's envisioned microscopy. FIBs are an indispensable tool used on a wide range of applications comprising: microscopy, microimaging, nanoimaging, microfabrication, nanofabrication, microelectronics, characterization of metallurgical processes, polymers science, pharmaceutical tooling, ion-beam-enhanced deposition, micromachining, fabrication of microholes, microstructures, surface treatments, nano-manipulation of biological substrates. As few other remarkable examples, the applications of ion beams in Biotechnology span from cancer radiotherapy to beam-induced gene transfers.

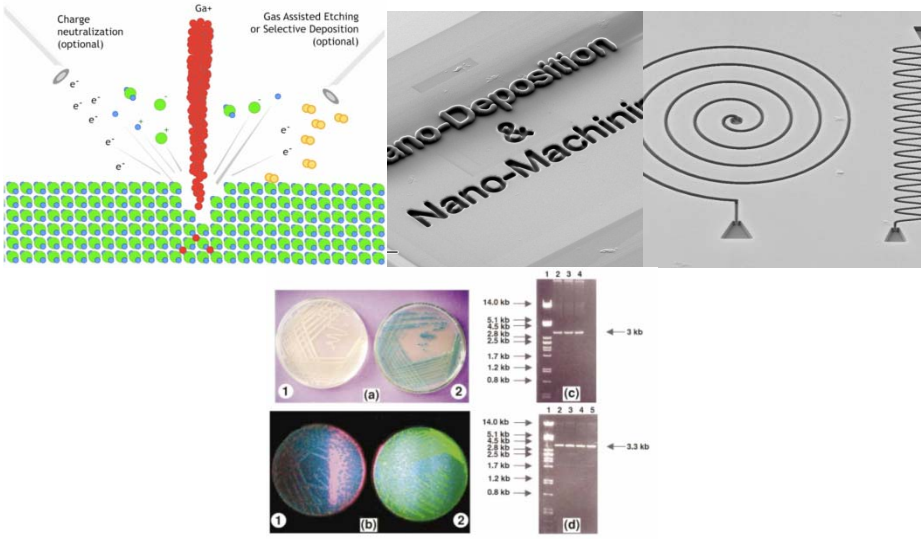


Fig 25: Common FIBs use beams of Ga, allowing machiningon micro- and nano-scale (examples of FIB applications)

<u>The present FIB systems and their limitations</u>.
Most of the FIB systems used nowdays are based on Liquid Metal Ion sources, with Gallium as a primary atom for the beam. The first Gallium FIB was developed during the second half of the 70s . The technology of Liquid Metal Ion sources was refined during '80s after many relevant pioneering explorations, like Sudraud, Mair, Prewett, Melngailis. Commercial devices became a reality during the '90s; nowadays the already-large number of applications of FIBs is still extending, covering

many fields of applied science. However, the sources based on Liquid Metal Ions of Gallium have many drawbacks. The Gallium implants into the structure of the bombarded surface of the sample, and in many applications like microelectronics, Gallium implantation is not acceptable. Other ion beams using materials different than Gallium are thus desirable.

Having a greater chemical versatility on a FIB device means opening the roads toward a wide range of new applications on which ion species can be chosen not thinking about technology limitation of FIB, but based on the specific need of the process. The current alternative to Gallium-based FIB systems is represented by setups using Wien filters. A Wien filter uses ExB mass filtering to select the desired atom from a source of multiple metals. FIB systems able to operate with elements other than Gallium comprise Si, Cr, Fe, Co, Ni, Ge, In, Sn, Au, Pb. The other relevant FIB system using elements different from metals is represented by the Helium Ion microscope, used as an alternative to SEM for high-resolution microscopy. Current research frontiers on FIBs are trying to expand the range of elements used in ion beams.

The FIB system based on S-helicon could offer a great versatility and control of the ejected beam and, most important, should be able to operate with a wider range of chemical elements than those used in current FIB technologies, thus offering a tangible next step toward the extension of chemical applicability of FIB systems. Moreover this device doesn't apply electrodes, thus strongly reducing issues related to contamination.

Applications to plasma treatment
The technology invented in HPH.com project based on S-Helicon antenna is suitable to be applied also in the frame of plasma treatment allowing much lower power respect to standard plasma source. In Fig. 26 is presented an industrial source developed at UNIPD-CISAS based on the newly technology for surface treatment which allow for power reduction of at least 50 % respect to standard source. Moreover, it can be operated with many different types of gasses including chemical aggressive and oxidant species.

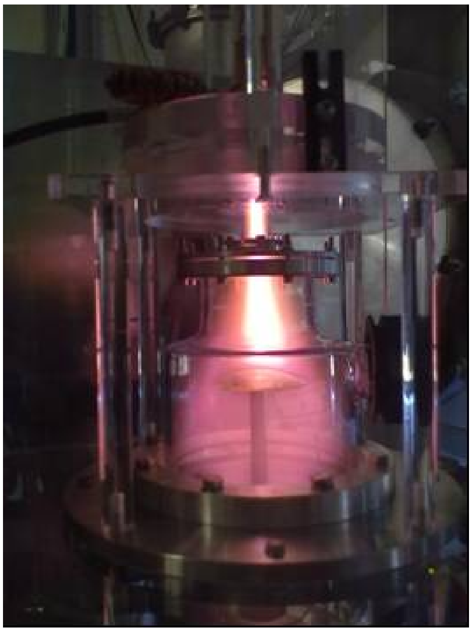


Fig 26 Plasma source implemented at University of Padua-CISAS to study surface modification due to plasma surface interaction using S-Helicon antenna.

1.4.2 New generation of propulsion systems

The thruster family based on the HPH.com technology, will allow for a **big step** in the propulsion field thanks to the following remarkable capabilities:

High performances. The high power version of HPH.com will potentially put HPH.com thruster in the top gear of the current propulsion system

Intrinsic simplicity and reliability: it is simple as an helicon thruster but much more performing,

Very **compact dimension**: it will allow a power density higher than any other propulsion system.

Capability of working with generic gas, thus it will be able to operate also with residuals of chemical fuel or oxidizer with no needs of new reservoir or with gas taken form planet atmosphere. This feature could have a strong relevant impact also on **future human-spacecraft** and **space stations** allowing the combination between the propulsion systems with the human life, **recycling human waste**. It is interesting to note that on the International Space Station, there could be enough methane produced to fuel a smaller lander to go to the moon. Methane is a product of life support systems when the CO2 is removed through the Sabatier process and water is recovered. Looking forward to Mars, oxygen and methane are also good candidates for **In-Situ Resource Utilization** (ISRU) technologies that produce propellants on the surface of Mars.

The capability of working with generic gas allows also this system to operate in the air-breathing regime thus allowing for in-orbit propellant utilization. Thus this technology combined with atmospheric intake and storing system could potentially introduce revolutionary new missions with of “unlimited “ duration.

Low cost assembly, HPH.com have been conceived to minimize cost of the thruster itself and also the Power Processing Unit, in order to allow applications onboard mini satellite. The target is to power small satellite, currently completely passive, allowing for maneuvers, thus strongly increasing mission versatility.

1.4.3 New low-cost demonstration scenarios

One of the main difficulties for the HPH.com thruster in orbit demonstration is to keep low the mission costs. In order to achieve this goal is needed to use a competitive platform such us for example an university microsatellite and design and perform a low cost mission.
The platform designed and manufactured by GAUSS team- UNIROMA1, using commercial of the shelf sensors, homemade solar panels, magnetic active attitude control system and maintaining limited the satellite weight, allows to have a low-cost bus for in orbit demonstrations.

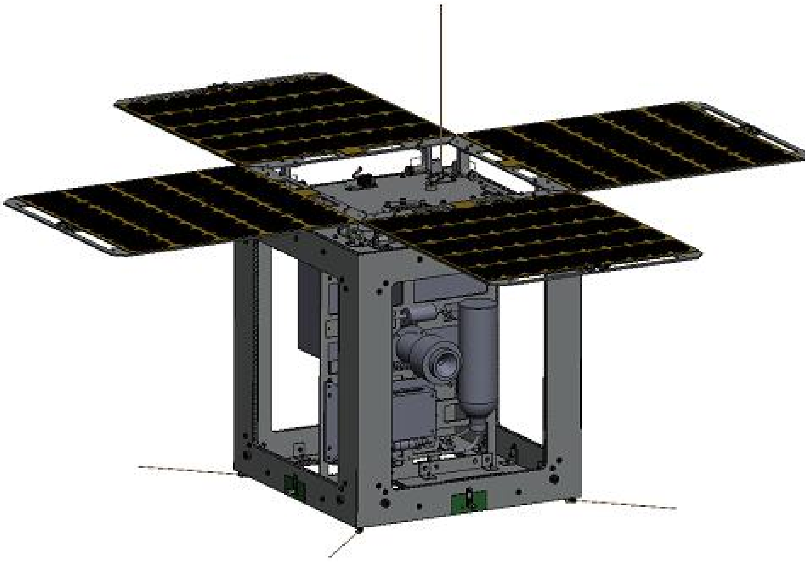


Figure 27 HPH.com microsatellite Final Configuration

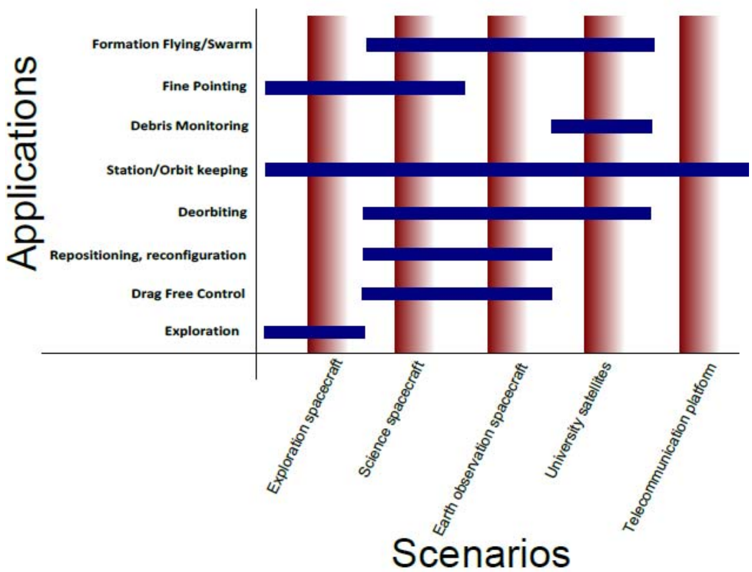
In addition the GAUSS team has suggested performing a particular kind of mission that allows maximizing the HPH.com satellite performances. The suggested orbit is a Sun Synchronous Orbit dawn-dusk orbit, so the satellite will always exposed to the Sun. Due the small size of the microsatellite one of the most critical issue is the power generation.

The study shown that minisatellite are a viable options for low cost demonstration missions able to provide a proper operative environment for the thrusters and an accurate test bad to characterize its performances.

1.4.4 New mission architecture and opportunities

New mission scenarios

The HPH.com is potentially suited for a variety of applications. Scalability, long life time, throttability, versatility appears to be its major characteristics and in this perspective the usage of the HPT could provide a benefit for current, and future mission concepts and applications.



Different scenarios can be identified (i.e. Exploration, Science, Earth Obs., Telecom, University) but inside each of them it is possible to identify many cross-applications in which the HPT can provide benefit, for example drag free control, formation flight, pointing, etc.

Each of these applications has different requirements, but the versatility of the HPT could potentially bring benefits to many of them. As an example the scalability of HPTs is able to design low power thrusters useful to Formation

Flight, but also a scale up can results in medium to high power level thrusters with higher thrust level for the Station Keeping application.

Other than the missions that are currently in place, there are other mission concepts that could be supported by the helicon thruster technology, because of its scalability and versatility. The most important ones are:

- Debris Removal
- Orbital refueling at spacecraft EOL
- Manned Explorations to Mars (and Moon)

Enabling technologies

Further mission concepts that could be also investigated are those applying the air-breathing capability.
In fact helicon thruster may allow also new extended and versatile mission scenarios based on the capability of operating with different type of gasses and high lifetime. The working principle of the proposed gas accumulator system is the following: while orbiting around a planet the spacecraft follows a low altitude trajectory in order to cross the upper layer of the atmosphere. The incident gas flow is collected and dynamically compressed by the intake. A pumping system further compresses the collected gas bringing it to the pressure required by the pressure reservoir. A flow control system subdivides the mass flow between the tank, where it is stored to be later employed during eventual out-of-atmosphere flight, and the thruster, which continuously operates in order to compensate the atmospheric drag.

New appealing mission concepts can be enabled by this approach, having spacecraft providing very long servicing operation around earth for LEO missions, or even very long and variegate exploration missions around planets with atmosphere.