EXPERIMENTAL SET-UP TO TEST A 50 W HELICON PLASMA THRUSTER

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Abstract: **This paper describes the experimental layout under development to test a helicon plasma thruster for a small satellite. The thruster class is 50 W 1mN. This work is done within the research project Helicon Plasma Hydrazine Combined Micro (HPH.com) in the frame of the 7th Framework Programme of the EU by a European consortium. Experimental tests are foreseen to validate codes, to support thruster design and to verify thruster performances. Two different test beds will be designed, an engineering model and a**

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qualification model. Tests will be conducted at CISAS and ONERA. The experimental layout and the diagnostic set-up, currently under design, is presented in the following paper.

I. Introduction

THE objective of the HPH.com research program (Helicon Plasma Hydrazine combined micro) is to design, optimize and develop a space plasma thruster based on helicon-radio-frequency technology and its application to a mini-satellite for attitude and position control (Figure 1). Moreover, a detailed feasibility study will be also conducted to evaluate the possibility of using the plasma thruster to heat and or decompose a secondary propellant, in order to develop a two mode thruster, high-efficiency low-thrust plasma-thruster mode and a low-efficiency high-trust secondary-propellant-plasma–enhanced mode.

Target of this research program are applications in the range of 50 W power. Expected thruster performance are: 1.5 mN of thrust and $I_{sp} > 1200$ s. HPH.com will develop through the following steps:

a) Deep numerical-theoretical investigation through dedicated plasma-simulation tools;

b) Extensive experimental campaign to validate codes, to investigate the physics phenomena involved and to prove thruster performance;

c) The development of a full-scale thruster-prototype to be mounted on board of a mini-satellite to demonstrate technology feasibility;

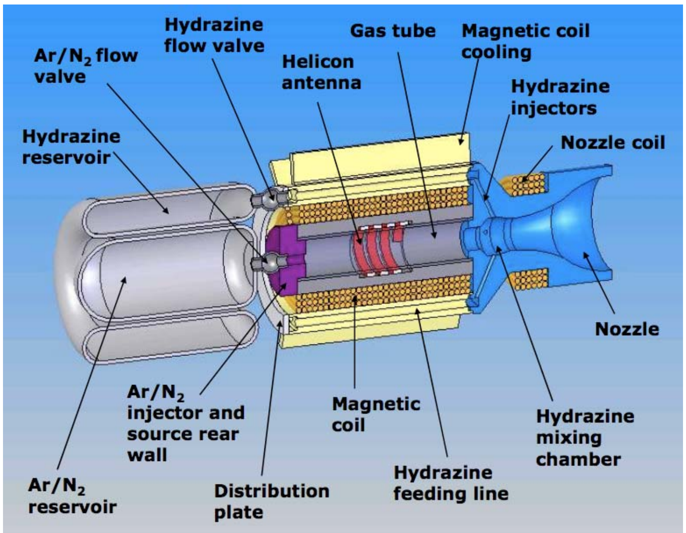

Figure 1. Schematics of the HPH.com helicon thruster.

d) The study of all the critical issues related to the application to a mini-satellite;

e) The design and manufacturing of the mini-satellite mock up including all critical components;

f) Analysis of scaling law to lower and higher power;

As a final results of the project, a detailed analysis will be conducted in order to evaluate the possible application of the thruster in space missions requiring low-thrust accurate-attitude and position control. The project is started December 2008 and is currently ongoing. In this paper is presented an overview of the experimental activities under development.

II. Review of existing experimental set-up

Several helicon experiments have been developed in the past years aiming at developing efficient plasma source for industrial applications and space propulsion. The experimental layout can be classified in two main classes: (i) helicon source mounted externally with respect to the main vacuum chamber[1], and (ii) helicon source mounted internally the main vacuum chamber[2-6].

Magnetic field is generated both with coils [1-4 6-9] and permanent magnets [5,10,13]. Magnetic field strength varies form low magnetic field[2] (lower than 100 Gauss) medium[2,3,4,7,8,11,18] (between 100-1000 G) and high[1,5,6,10,14,15] (>1000 G). Enhancement of plasma density using non-uniform magnetic field has been identified by Braginky[7], Shamrai[10], Yoshitaka[9]. Increasing on magnetic field strength has been achieved Shinohara[19] using a suitable magnetic circuit placed outside the source.

The antenna set-up varies through different well know helicon antenna configurations however the most common are helical [1,2,3,6,9] Nagoya III [3-5,6], Boswell 7[,8,18] bifilar antenna was used by Miljak[4], Gillard [6] tested both helical, Nagoya III and modified Nagoya a single and a 4-loop spiral antennae.

The antenna is most of the time fed by a L-matching network operating at 13.56 MHz. Operations in the range 20-30 MHz has been studied by Miljak[4], Toki [18],Chen [13], 10-100 MHz range was studied by Eom[5] in a remarkable low power regime (20-100 W), Toki[8,18].

Standard diagnostic of plasma sources is normally based on compensated Langmuir probes set-up to scan plasmas radially or axially, spectrometer[1], CCD cameras[3], and microwave interferometers[9]. Magnetic probe has been also applied to analyze the helicon field [4,7,16]. The plasma beam is studied using moveable Mach probes[1,14], with RPAs [1,2,7,10,11] and LIF[15].

III. Model philosophy

Experimental activities are a fundamental step in HPH.com research program. The experimental test bed is under development aiming at:

(i) Code validation: several tests are planned in order to validate the codes under development.
(ii) Thruster analysis and optimization
(iii) Thruster performance characterization

Two experimental models will be developed: engineering model (EM), and qualification model (QM). The EM will be representative only of the main assembly of the thruster (i.e., it will be based on a plasma source having size in the expected range, it will implement magnetic field in the range of the expected range) and will be expressly designed to allow code validation and system development (thus the plasma source must be easy to be replaced, the magnetic field intensity an configuration must be easily changed, etc.). The QM will be designed according to a thruster optimization and analysis procedure; it will be representative of the real flight hardware. QM model will be designed by KHAI and is foreseen for the middle of 2011.

The engineering model will be developed in two different version, one to be tested at CISAS facility, designed to be applied externally to the vacuum chamber, and one to be tested at ONERA, expressly designed to be assembled inside the vacuum chamber.

IV. Experimental set-up at CISAS

CISAS facility is current based on a 0.8 m^3 expansion chamber with the plasma source externally mounted. The facility is currently pumped with a Lebold turbo molecular pump having a pumping speed of 500 l/s.

The experimental set-up at CISAS will be fully instrumented in order to analyze plasma evolution within the source and the acceleration region. The facility will be equipped with the following instrumentations: Langmuir probe, microwave interferometer, several spectrometers located in different part of the plasma source in order to characterize source behavior, optical camera to provide a general overview of plasmas behavior, an finally a retarding potential analyzer and a Mach probe to characterize the plasma beam. Some diagnostic equipment will be movable to scan different plasma source locations. A management electronic will acquire the all diagnostics and will control the all robotic arms.

Figure 1. Current CISAS experimental set-up with Helmholtz-magnetic-coils.

The experimental layout at CISAS is presented in the following picture

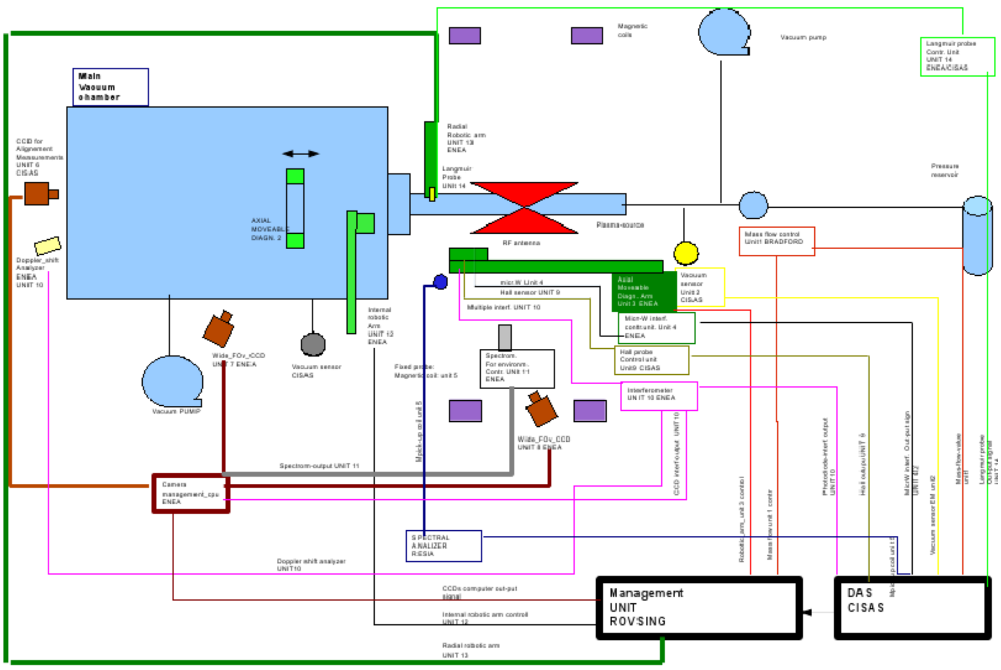

Figure 2. Schematics of the HPH.com Engineering model experiment.

A. Diagnostics

The physical parameters of the Helicon plasma and of the detached plume will be measured by several diagnostic systems, which are presently under development. The achievements in RF coupling and specific impulse will be evaluated through the knowledge of the plasma temperature and density, ionization degree, impurity contamination, uniformity etc. that will be input to the simulation codes. For some measurements (e.g. Interferometry) the small plasma dimensions (r~15mm) rules out any possible spatial resolution across the plasma section, so the information on spatial profiles will be obtained by combining data from more diagnostics in the same longitudinal (along the plasma tube) location.

1. Microwave interferometer

The density of the plasma, which is physically related to its refraction index, can be evaluated by measuring the phase delay of a wave traveling across the plasma section. The measurement can be done by a microwave interferometer whose emitting and receiving horns face the plasma tube. The design of the interferometer takes into account the density range of interest (10^{17}<ne<10^{19} m^{-3}), which sets a lower bound to the working frequency (to avoid the wave's cut off) and demands a high precision in the phase measurement. These requirements can be met by a 75GHz oscillator and a digital phase comparator with a 0.2° sensitivity. (See Fig. A)

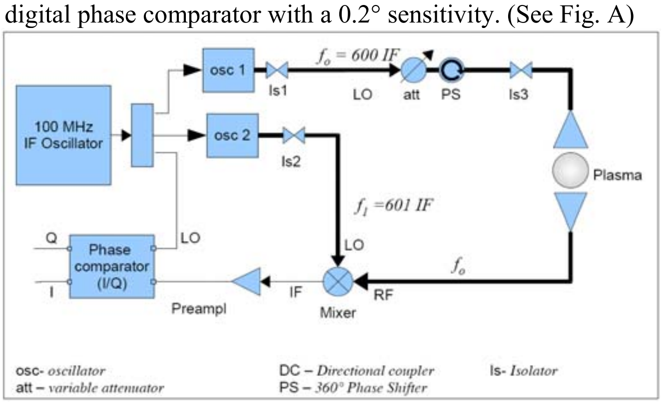

Figure 3: Scheme of the proposed interferometer

2. Langmuir probes

A local measurement of the plasma density can be obtained by the use of Langmuir probes..

For preliminary evaluations, a provisional radial probe with a 0.25 mm Mo filament parallel to the longitudinal magnetic field, battery biased, will scan radially the plasma and provide the electron saturation current and consequently the neTe product.

When acquiring the probe I/V characteristic in a RF plasma sources there are some difficult in the interpretation of data because (1) the plasma potential oscillates and (2) connection cables pick up of the electro-magnetic field emitted by the antenna. The EM field generates a noise RF signal superimposed to the probe current.

To suppress the RF signal disturbance and to compensate the plasma potential oscillation, a special conditioning filter has been developed to be applied between the probe and the I/V conversion device. The filter is specifically designed to offer a very high input impedance and low output impedance to RF signal harmonics.

3. Spectrometers

Important information on the ionization degree and on the electron density can also be obtained by the study of the ion equilibrium in the plasma. In the temperature ranges expected (5-10 eV), Ar will mainly emit the Ar I and Ar II lines, which can both be observed in the visible range. The local emitted brightness can be modeled by simulating the ion equilibrium balance at given temperatures. The emission profiles will be obtained experimentally by a set of 3-5 spectrometers observing the plasma through Ø1mm optical fibers. The spatial resolution imposed by the optics will be ~3mm. In order to guarantee consistent measurements, we require that the optical measurements correspond to the same longitudinal positions of the interferometer for this reason all the fibers will be conveyed to unique optical head, integrated in the interferometer holder. There will one spectrometer per each line of sight. Miniature spectrometers with resolution 0.02 nm have been already tested on the provisional installation giving satisfactory responsivities in typical experimental conditions (Fig.4).

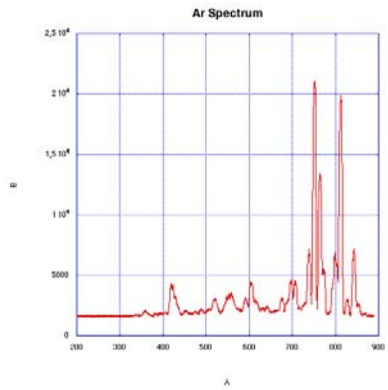

Figure 4: Ar Spectrum in the current experimental situation

4. CCD cameras

Possible non-uniformities in the plasma, induced by the shape of the antenna or else, will be monitored by standard rate video cameras. Data will be acquired digitally and stored in files so that the brightness of any region of interest can related to other measurements. The cameras can be equipped with interference filters on the Ar I line. The plume will also be observed by cameras, giving a direct estimate of the divergence of the plume. (Fig.5)

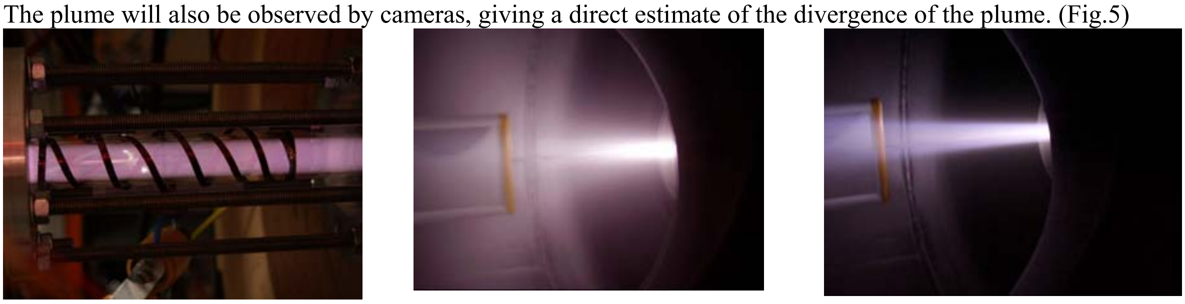

Figure 5: Preliminary pictures of the source and the plume region at 10-30 W operation at CISAS.

5. *Mass Flow Control Equipment*

The mass flow control equipment consists of a thermal mass flow sensor and a flow control valve. The mass flow sensor provides the feedback signal for control of the flow control valve through a set of intermediate acquisition and control electronics.

The flow sensor is based on an existing model developed by Bradford Engineering in the GOCE-PXFA and GAIA programs. This heritage model is capable of measuring flow rates up to 2.5 mg/s GN2 (adaptive) with a resolution of 0.0007 mg/s (accuracy 0.5 %R + 0.1 %FS). Unlike other flow sensors which are based on a thermal principle, this flow sensor has a response time down to 25 milliseconds, with room for improvement.

The flow sensor has the sensing element located in a by-pass. By changing the ratio of hydraulic resistance between the by-pass sensing element and the main passage, the flow rate range can be tuned to the customer requirement while retaining the typical exponential response curve and hence fast response times. Since the sensor's principle is based on the direct measurement of the mass rate and its thermal capacity, the sensor can be tuned for use with different gases than xenon, such as argon, neon, or mixtures of these gases as required for application in HPH.com.

Each MFS includes a set of electronics to provide the proper power and signal interfaces and the sensor signal acceleration.

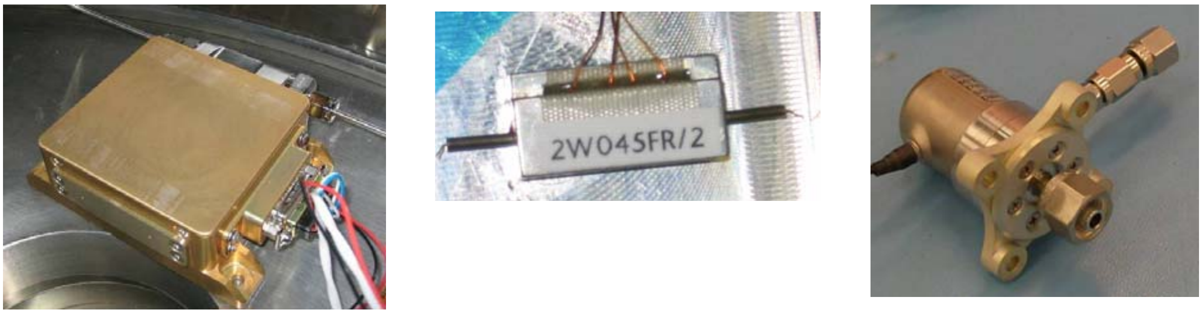

Figure 6: Micro flow sensor and sensing element (mass: 419 g, envelope 37 x 113 x 120 mm) and proportional flow control valve (mass: 175 g, envelope 31 x 51 mm) on the left.

The flow control valve is based on the proportional micro thruster, which has been developed and qualified by Bradford Engineering in the course of the GAIA program and is baselined for both the Bepi Colombo and SGEO electric propulsion subsystem flow control units. Due to its generic design, the nozzle at the exit of the valve can be replaced a weldable tube stub, which allows it to be used as a flow control valve. The salient feature of the design is the proportional action of the valve mechanism, which makes it perfectly suited for use in flow control applications.

The simple design of the valve is reflected in the required electrical interfaces: the flow control valve is driven by an analog voltage in the range of from 0 to 15 Vdc (adaptive) proportional to the desired mass flow rate, therefore no additional power conversion/conditioning electronics are required. With a valve response time of 13 msec in combination with the fast response of the flow sensor, the flow can be accurately controlled in closed loop.

6. *Power supply*

At the typical working frequencies, the impedance of Helicon antennas is mainly inductive and its impedance value can differ from the output impedance of the power amplifier (Ro = 50 Omega). The impedance mismatch between the amplifier and the antenna causes a non-efficient power transfer from the amplifier to the antenna, mainly due to (i) power reflection from the antenna to the generator and (ii) reactive power flowing through the power line.

Due to the previous points, a lack of power occurs, moreover the electrical system must be oversize compared to the amount of power transmitted to the antenna.

It becomes necessary to use an impedance matching circuit, in order to reduce the power losses in the connection cables between the amplifier and the antenna.

The traditional matching circuits used in ground applications (Matching-boxes) are usually based on a pair of variable reactive components (capacitors) that create a resonant load with the antenna.

The antenna impedance shows a strong dependence from the characteristics of the plasma inside of it and in particular a wide change in the antenna impedance occurs when the plasma generation starts. So an electromechanical intervent is needed to adjust the value of reactive components, in order to maintain the perfect matching condition.

A new matching system is being developed, that allow keeping the perfect matching condition, in order to avoid the use of electromechanical components. Operation in the range 1-100 MHz is foreseen.

7. Management Unit

The Management Unit provided by Rovsing is in charge of making the parts of the experiment work together. This includes control of actuators like the robotic arms and control of the mass flow unit. It also includes handling of measurement data in cooperation with the Data Acquisition System (DAS) provided by CISAS. Handling of measurement data in turn includes collection, storage, analysis, and visualization.

The Management Unit provides a central Graphical User Interface (GUI) which allows an operator to set up, initiate, control, and monitor experiments. Furthermore, the Management Unit allows the operator to perform analysis and visualization of experimental results. Finally, the Management Unit provides external access to measurement data, thus allowing performing further analysis using external tools.

The Management Unit comprises a central process and a number of interface processes. The central process runs on a computer dedicated for the Management Unit. The interface processes may run on the same or on other computers and are connected to the central process via TCP/IP. The central process runs the GUI which comprises a single work station (one keyboard, one mouse, and a number of screens). The interface processes are capable of controlling parts of the experiment such as robotic arms and are capable of collecting measurement data. A special interface process takes care of communications with the DAS. Another special interface process provides external access to measurement data.

The central process of the Management Unit comprises a fixed core and dynamically defined add-on units. The add-on units are responsible for computation of derived signals and visualization. Computation of a derived signal may involve simple operations like conversion of an uncalibrated signal into a calibrated counterpart or more complicated operations which involve arbitrary computations on an arbitrary number of raw or derived signals. Likewise, visualization may involve simple visualization like plotting a measured value versus time or more complicated operations which involve arbitrary computations on an arbitrary number of signals.

To cope with the dynamic and unforeseeable nature of experimentation, add-on units are stored as raw text, allowing advanced operators to modify and extend the system dynamically.

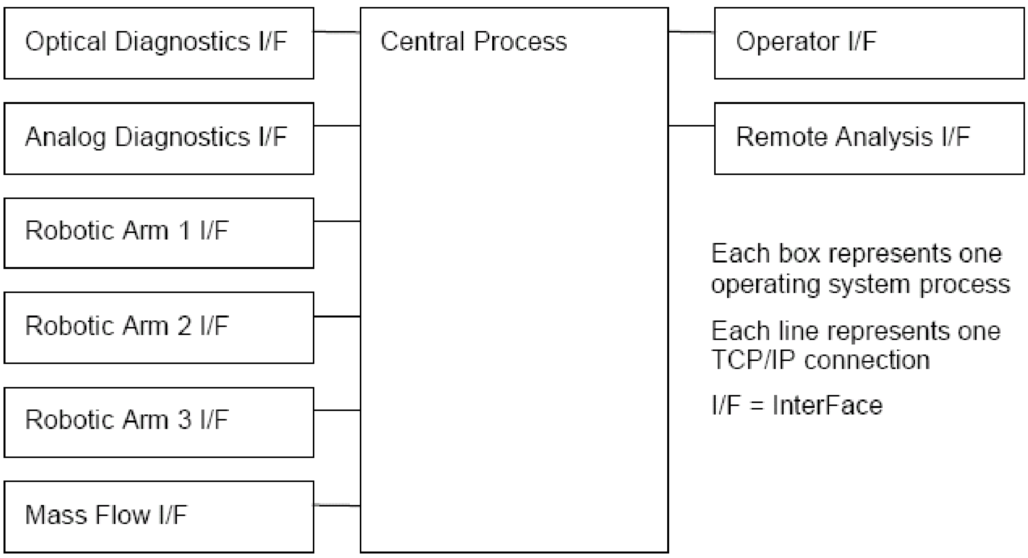

Figure 7: Management Unit top level architecture

8. *Experimental set-up at ONERA*

In order to fully characterize the physics and performance of the thruster, several characterization campaigns will take place at Onera in Palaiseau (France). The data obtained will also serve for code validation, which will be used in further iterations of the thruster design.

Using ONERA extensive experience in thruster testing, three main diagnostics will be used:

- thrust measurement (0.1 µN to 100 mN possible)
- plume characterization with electrostatic probes (RPA)
- plume characterization with non-intrusive optical methods (emission spectroscopy, Doppler Laser Induced Fluorescence).

The measurements will be made during thrusters firing in one of the two Onera vacuum test facilities. The tanks have a variety of electrical, optical and fluid feedthroughs in order to accommodate different thrusters and advanced experimental setups.

The B61 facility is a chamber 1 meter and diameter and 4 meter long, fitted with an auxiliary chamber 1 meter long and 60 cm in diameter that is linked to the main chamber via a gate valve 50 cm in diameter. The experimental setup would be placed in the auxiliary tank. Pumping is performed by a turbo-pump and a cryogenic pump at 33 K (total pumping rate: 2000 l/s for Ar and N2, 8000 l/s for Xe). The limit vacuum obtained is < 10-7 mbar.

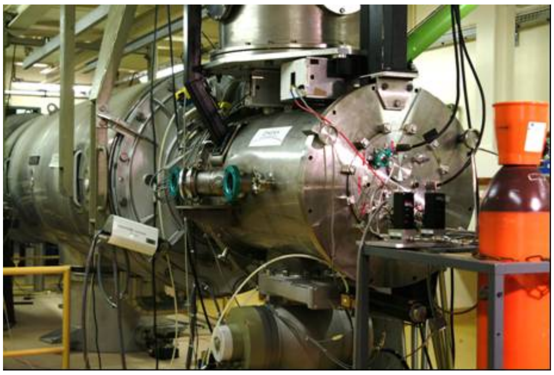

Figure 8: ONERA B9 (left) and B61(right) test facility.

The B9 facility is a new chamber, currently in test. It is 2 meter long and 80 cm in diameter. It offers a significantly wider working diameter than the B61 (80 cm versus 60 cm), which is critical when fitting a thruster with different optical, laser and mechanical components. A turbopump is used (total pumping rate: 2000 l/s for Ar and N2, 1000 l/s for Xe).

The thrust measurement will be performed with one of the two ONERA thrust balances, depending on the thrust level. A micronewton balance has been developed at Onera since 1999, and has achieved thrust resolution better than 0.1 µN with a cold gas thruster from Bradford Engineering. The range is 3 mN. An improved model is being developed in the framework of this study, in order to accommodate the larger, heavier helicon thruster. The calibration of the thrust with this balance is absolute as it uses calibrated weights to simulate known thrust levels. Electrical and fluid connections are always a challenge on micronewton balances and will be addressed. This balance will be mounted in the B9 vacuum tank.

A millinewton balance is also available, and is mounted in the B61 vacuum tank. It is a commercial model with 1 mN resolution and a range of about 200 mN. It has been successfully used in the past with an SPT50 thruster.

Electrical plume characterization will be performed using electrical probes (RPA - Retarding Potential Analyzer) that will be developed and installed in the B9 tank on a mobile platform to scan the plume. This will give the spatial distribution, with moderate spatial resolution, of the ion flux and mean energy.

Optical diagnostics have been shown to be the most powerful to probe a plume for precise parameters while being non-intrusive. If emission spectroscopy can give insight in some of the physics of the plume, the powerful Laser Induced Fluorescence can be used for precise velocity vector and density measurements. At ONERA an optical setup has been built, and a demonstration has been made of 3D map measurement of the absolute density and average velocity vector of neutral cesium, point-by-point with a 1 mm spatial resolution. The demonstration has been made for cesium, and for Xenon in a simpler setup. For Argon, which is the gas used in the proposed helicon thruster, the literature shows that the spectroscopic features and the needed laser sources exist for an experiment that would give the 3D distribution of velocity vectors of Argon ions (and also argon neutrals if needed) in the plume. These measurements will be key to understanding the physics of the plume and validate the code, especially the detachment code (giving the vector orientation) and the ion acceleration mechanism (giving the velocity magnitude). These experiments will allow to precisely measure the real performances and characteristics of the thruster.

V. Conclusion

The experimental set-up under development at CISAS and ONERA to support the development of a 50W power helicon thruster under the 7th Framework Programme of the EU is presented. The diagnostic under development is based on Langmuir probes, microwave interferometers, spectrometers, retarding potential analyzer, Mach probes, thrust balance, LIF. The experimental set-up is foreseen by middle of 2011.

Acknowledgments

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