

## THE NEW EP TEST FACILITIES AT CENTROSPAZIO AND ALTA

M. Andrenucci <sup>1</sup>, M. Berti <sup>1</sup>, L. Biagioni <sup>2</sup>, U. Cesari <sup>2</sup>, R. Falorni <sup>2</sup>, L. Milaneschi <sup>2</sup>, and M. Saverdi <sup>2</sup>

(1) Centrosazio-CPR, Pisa (Italy)

(2) Alta S.p.a., 56121 Ospedaletto, Pisa (Italy). Email: alta@alta-space.com

### ABSTRACT

*Since 2000 a considerable effort has been undertaken by Centrosazio and Alta in order to jointly develop and install a new range of Electric Propulsion System (EPS) test facilities in Pisa, specifically targeted at advanced EPS testing. The new facilities were designed in order to provide advanced, high performance test benches for both fundamental research and industrial development needs. The first facility to become operative was the IV-4 chamber, which has been undergoing vacuum tests since late 2000 and has been fully qualified for EPS testing during the first half of 2002, using an advanced engineering model 2 kW Hall thruster. During 2001 the realization of a very large facility (IPP) for EPS and system level tests was initiated and it will undergo acceptance tests during the summer of 2003. The paper will present the design process of the different facilities, together with a full set of validation data for the IV-4 facility, as obtained during the qualification tests performed using the engineering model 2 kW thruster and a lab model 5 kW one: these include vacuum and pumping data (including the effect of advanced pumping cavity configurations), thermal behaviour of the target and of the pumping surfaces, etc A brief description of the facility subsystems dedicated to the EP diagnostics will also be provided.*

### 1. INTRODUCTION

Electric propulsion represents one of the most promising technologies for application in present and future space missions. Among the proposed concepts, Hall Effect Thrusters (HET) and Gridded Ion Engines (GIE) are particularly attractive for their interesting characteristics and performance. Presently, medium power Electric Propulsion Systems (EPS) in the 3-5 kW power range are proposed for a large class of primary propulsion applications, such as high altitude orbit raising, orbit transfer and high impulse interplanetary scientific missions (such as ESA's *Bepi Colombo* Cornerstone-class and *Solar Orbiter* Flexi-class missions). In the near future, interest is growing for GTO (or MEO) to GEO orbit transfers by means of high power EPS rated in the 10-15 kW power range, as shown by the recent trend in the satellite and EPS markets.

Despite of their promising performance, one of the main drawbacks in developing new high power single thrusters or clustered configurations is represented by the characterisation and qualification phases they have to pass before they could be accepted for integration in the space vehicle design. Moreover ever growing interest is being shown in EPS demonstration at vehicle level to assess the impact of EPS on the spacecraft's full operating configuration. All this, as thruster power increases, poses more stringent requirements on the vacuum facilities in terms of free volume, pumping speed and heat removal rate, cleanliness and diagnostic equipment in order to achieve accurate measurements of thruster performance and lifetime.

Since few years Centrosazio-CPR and Alta S.p.a., with the support of the European Space Agency and the Italian Space Agency, have been spending several efforts to procure and install a new set of highly performing facilities, suited for the characterisation and qualification of middle/high power EPS from the European space research and industrial community.

### 2. DRIVING REQUIREMENTS FOR FACILITY DESIGN

Centrosazio-CPR/Alta's vacuum facilities have been designed to respond to the precise increasing demand for EPS test benches. It's clear how the driving design specifications have been directly derived from the requirements for a reliable electric thruster characterization, endurance and acceptance testing. They can be easily summarized in reducing to a minimum the interactions between the thruster and the surrounding environment specifically including mechanical and electromagnetic aspects.

The dimensions of the chambers, length and diameter, are of course the primary design characteristics to be defined in order to allow the free expansion of the beam keeping the point of particles impingement as far as possible from the thruster. This usually ensures also adequate distances between the thruster and the walls for limited distortion of the applied electric and magnetic fields and a low contamination rate due to back-sputtering. Some semi-empirical formulas, developed in the past (specifically for HETs) by Russian scientists helps in preliminarily sizing the chamber in terms of free volume and of the ratio L/D as a function of the thruster's target power.

The reduction of mechanical interactions includes also a proper selection of low outgassing, low sputtering materials with a low relative magnetic permeability for the tank walls. Stainless steel (e.g. AISI 304 or 316 grades) with integral graphite lining usually satisfies all these requirements. Surface finishing also plays an important role for outgas rate, and must be correctly addressed selecting grades ranging from micropeening (mean roughness  $<1\pm 2 \mu\text{m}$ ) to electro-polishing for ultra-high vacuum requirements ( $p < 10^{-8}$  mbar).

Further to geometrical size, the ultimate (no mass flow) and the operational vacuum levels or equivalently the facility pumping speed need to be specified. Pumping capability is determined by the thruster operating requirements mainly to guarantee discharge stability and to reduce the effects of the background gas. In fact, background gas tends to improve the ground measured thruster performances on one side (Isp and thrust) due to mass re-injection, while on the other hand it increases the plume divergence due to CEX collisions causing anomalous reduction in thrust and increase in erosion and contamination. Since the operating and ultimate vacuum levels are strictly dependent on the thruster family ( $<10^{-5}$  mbar for GITs and  $<10^{-4}$  HETs are widely accepted) the chambers have been designed for a baseline thruster power class with large flexibility for successive upgrade to fulfil ever more tight pumping requirements.

Pumping systems (both for IV-4 and IPP) have three stages: primary vacuum (from atmospheric pressure to  $10^{-2}$  mbar), achieved by rotary and screw pumps, high vacuum ( $10^{-2}$  mbar to  $10^{-8}$  mbar) achieved by turbomolecular and commercial cryogenic pumps and finally high speed propellant pumping stage ( $10^{-5}$ – $10^{-6}$  mbar @ full gas load) achieved by large cryo-surfaces and LN2 cooled thermal shrouds. This latter stage is usually tailored, sizing the cryopanel active area and more generally the pumping cavity configuration (thermal shields, molecular diffusers etc.) in order to increase the effective pumping speed while keeping the running costs to a minimum. All the material and components have to be oil-free to reduce the risk of accidental contamination and to meet the requirements related to vacuum “quality” as specified by the maximum allowable partial pressure for non operating fluids ( $\text{H}_2\text{O}$ ,  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{H}_2$ ,  $\text{H}_n\text{C}_m$  etc.) adversely affecting the efficiency and the duration of critical and sensitive components such as the cathodes and/or the neutralizers.

The pumping system is autonomously driven by the in-house developed facility control system managing all the operations necessary to reach and maintain the high vacuum environment starting from ambient conditions. Several ionisation pressure gauges and mass spectrometers complete the pumping system for continuous monitoring of the operating environment.

Background pressure and back-sputtering rates are also greatly improved by peculiar shaping of the target element placed on the opposite side with respect to the thruster. The double conical shape in fact tends to reduce the amount of material back-sputtered towards the thruster directing it on the chamber lateral walls instead. In the same way impinging ions are reflected directly on the cryo-surfaces improving the pumping speed. Optimisation of the pumping system/cone shape was accomplished by PIC/DSMC codes to estimate the pressure distribution inside of the facility as shown in Fig. 12.

The facilities are completed by a set of subsystems including the cooling system for thermal shields, propellant feeding system, thrust stand, beam diagnostics, telescopic equipment for erosion assessment etc. for full characterization of the thruster performance. From this standpoint the facilities are designed to have a large number of flanges to offer the largest flexibility for thruster monitoring from simple visual inspection (including telescopic imaging) to beam spectroscopy, telescopic imaging, thermography and to several kinds of vacuum feed-through for propellant, power, signal (electrical or optical) transmission in or out of the chamber.

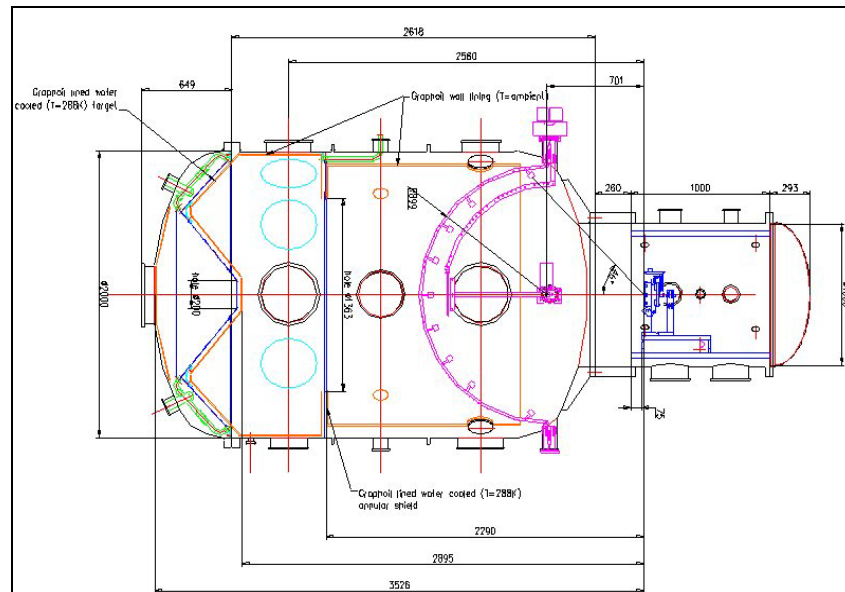
Finally the large space simulator IPP has been designed in order to accommodate, with only small changes in its basic configuration, different kinds of tests such as electric propulsion or thermal tests at spacecraft level. Maximization of the experiment turnover was another basic requirement for this facility in order to increase its utilization rate: for its configuration in fact two quasi-axial flanges ( $13^\circ$  wrt chamber axis), 600 mm dia., have been placed just aside of the main flange, 1m dia., aligned with the chamber axis, in order to prepare and even run different tests in parallel while the main test activity is ongoing on this privileged site.

In the following paragraph detailed description of the facilities, their subsystems and the measured performance of the facility IV-4, which served as subscale model of the IPP, will be given.

### **3. IV-4 TEST FACILITY DESCRIPTION**

Alta's IV-4 Test Facility was designed with the double aim of accommodating life tests of electric thrusters up to 2 kW and very short characterization tests up to 5 kW and of proving the effectiveness of the different technical features and design methods to be reproduced on a larger scale on the IPP vacuum facility. IV-4 is composed of two different bodies made of AISI 316L stainless steel, the auxiliary chamber (AC) 2 m dia., 3.2 m length and the small chamber (SC), 1 m dia. 1 m length. The two bodies are connected through a 1 m

dia. gate valve. The assembly of the AC and SC is shown in Fig. 1 where the main dimensions are also sketched.



**Fig. 1 IV-4 Facility Arrangement**

The small chamber is used to accommodate the thruster on the thrust stand and its electrical and gas feeding subsystems while the AC allows a free expansion of the plume reducing the interactions with chamber walls and accommodates the main pumping system. This configuration allows to execute long duration test on the thruster without exposing it to the atmosphere, because of the possibility to separate the two chambers by closing the valve while keeping a high vacuum environment in the SC with a dedicated secondary pumping system. In this way maintenance or repairing operations can be performed into the AC without interruption of the thruster exposition to the vacuum.

The chamber pumping system is composed of a primary pumping system located in the AC and a secondary pumping system located in the SC. The former consists of 1 Varian Triscroll PTS-600 primary pump (25 m<sup>3</sup>/hr), 1 Varian TurboVac 2000 VHT turbo pump (2000 l/s on N<sub>2</sub>), 1 Leybold Coolvac 3000 cryopump (3000 l/s on N<sub>2</sub> and 10000 l/s on H<sub>2</sub>O) for the first two vacuum stages, while the high speed stage is achieved by 7 Leybold CoolPower 150 cold heads (CHD). These cryo-generators are equipped with custom pumping surfaces made of OFHC copper insulated by multi-layer sheets on the passive side to reduce the adverse effects of radiative heating. In the high capacity configuration (for long duration tests) plates of 0.2 m<sup>2</sup> working at 35-40 K guarantee a pumping speed of 60,000 l/s on Xe, while the highest speed configuration (for short duration tests) larger plates of 0.4 m<sup>2</sup> at 40-50 K allow about 130,000 l/s on Xe with a reduced lifetime (about four time shorter) before regeneration. This operation is generally carried out sealing the thruster in the SC by the gate valve while maintaining the required high vacuum level by means of the secondary pumping system. Since in this case no gas load is present it simply consists of 1 Varian Triscroll PTS-600 rotary pump (25 mc/hr) and 1 Pfeiffer TPH240 turbo pump (240 l/s on N<sub>2</sub>).

The IV-4 chamber is also equipped with a series of monitoring devices consisting of 4 chamber pressure transducers (2 Inficon Sky90 + 1 Varian Eyesys + 1 Alcatel AHC 1010), 1 mass spectrometer Residual Gas Analyser (SRS RGA), 3 pumping system pressure transducers located on the turbo and cryo pumps (3 Varian Eyesys) and a large number (up to 64) cold heads' and target's temperature sensors (type-K thermocouples and RTD sensors). These items are fundamental for environmental monitoring and the location of some of them is shown in Fig. 2.

The AC features a conical target and a ring shaped guard disk both water cooled (in this case LN<sub>2</sub> shrouds were not required) primarily to remove the heat load (up to 5 kW) released by the plume on the chamber walls by impingement and to prevent the warming up of the cryo-surfaces both lowering the heat load irradiated from the chamber walls and shielding the direct view of thruster. The conical target proved to be very effective in reducing the thruster contamination due to back-sputtering as witnessed by the different depositions observed in the pumping cavity and near the thruster.

In Fig. 3 a view of the facility showing the Grafoil-lined conical target is presented on the left, a 5 kW HET prototype which was used in order to demonstrate high power operation is shown on the right.

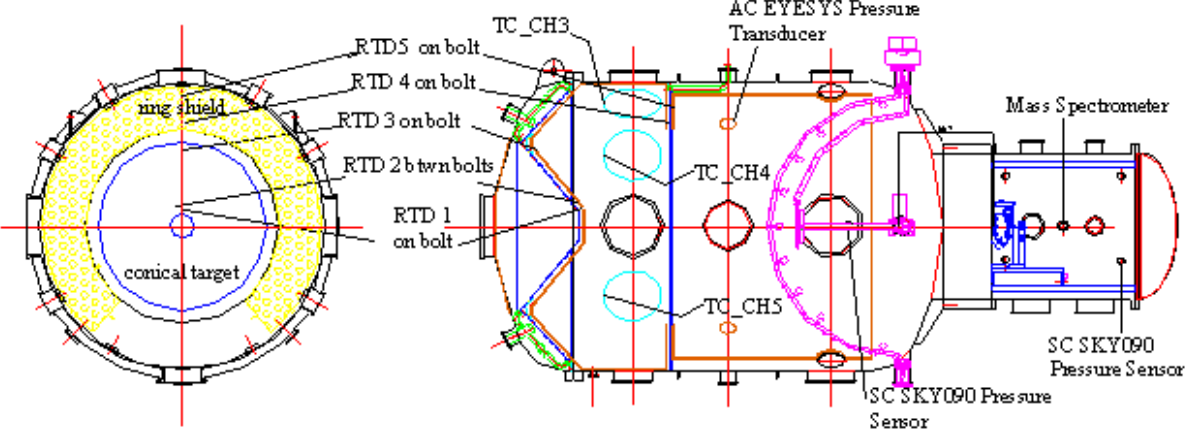


Fig. 2 Monitoring device locations

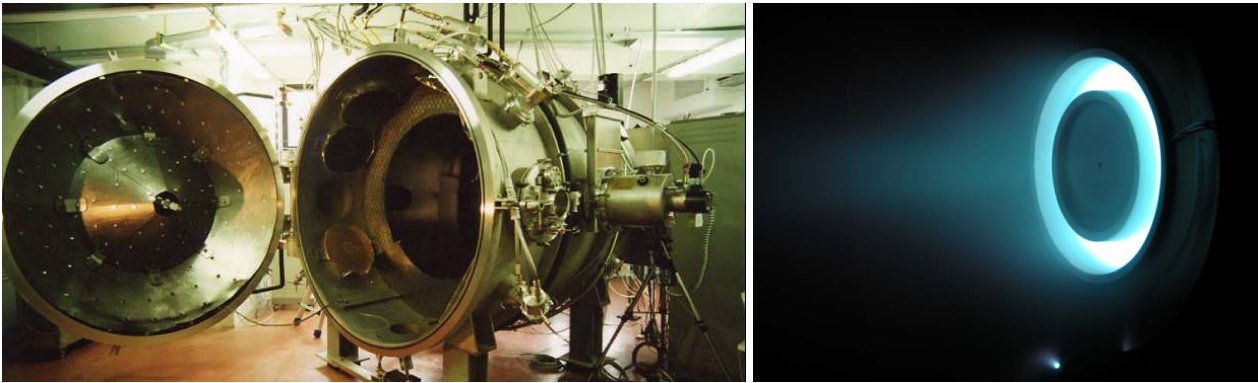


Fig. 3 Alta's IV-4 Vacuum Facility and a 5 kW HET prototype being operated in it.

The IV-4 diagnostic system dedicated to the experiment consists of a plume scanning system with electrostatic probes, a real-time plume centroid tracking system, a high precision one axis thrust stand, a telescopic imaging system for close up examination of the thruster during test (from different windows located at 0, 45 and about 120 degrees from the thruster axis) and conventional thermal and electric parameters monitoring devices.

The plume scanning subsystem consists on a movable circular rake, 1.6 m dia, bringing an array of collimated Faraday cups and RPA to measure the current density distribution around the thruster up to 90 degrees.

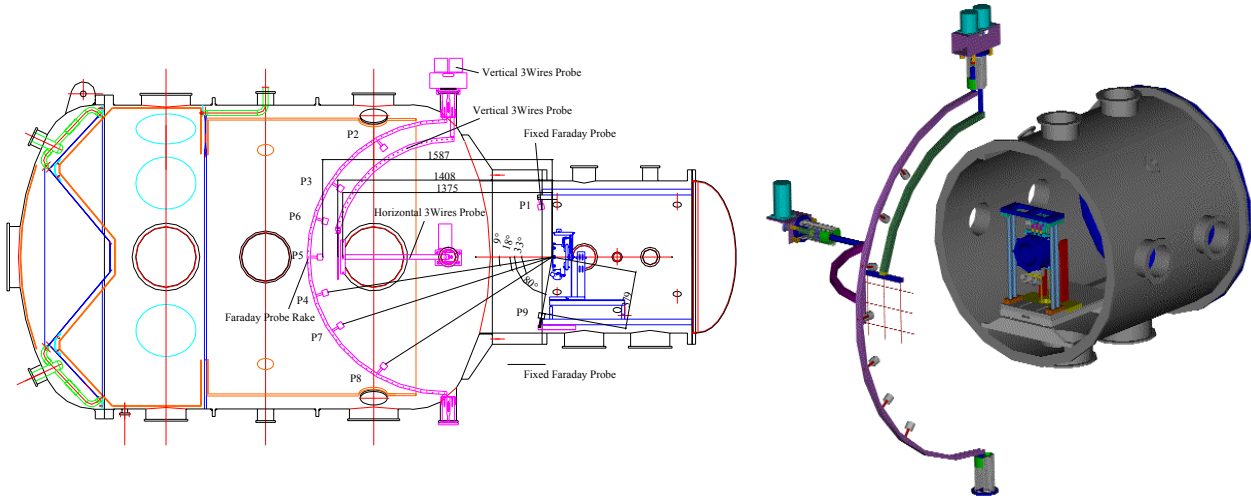


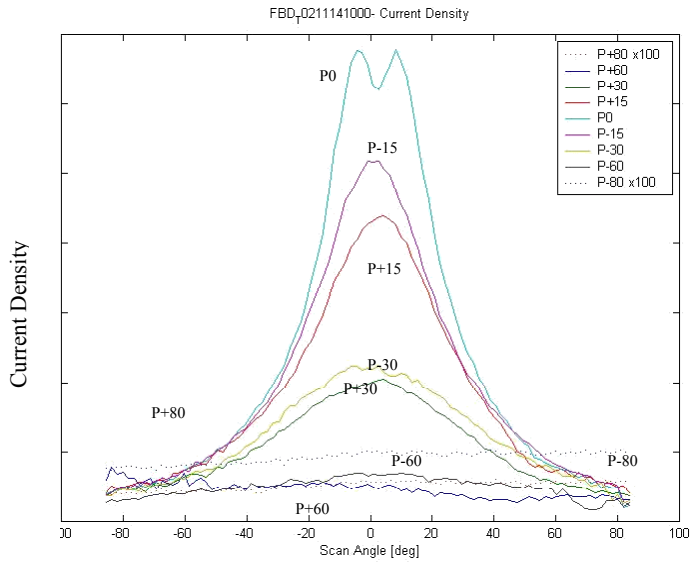
Fig. 4 Facility IV-4 beam diagnostics arrangement

The “thrust vector” tracking system consist on two independent rakes rotating around vertical and horizontal axes. The rakes bring on their tip a “three wire probe”, consisting on three long, negatively biased (-10÷-20

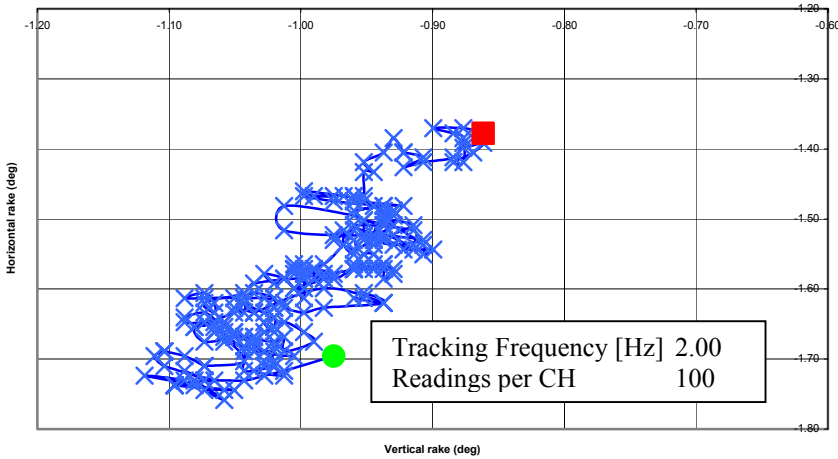
V) electrodes in order to collect purely ionic current. The wires are placed symmetrically with respect to the rakes, which are set in their initial position respectively in the vertical and horizontal plane of symmetry of the thruster. When a current unbalance is detected between the two external electrodes of each probe (the central wire is only used to refine the measurement or to double check the primary information) by the control system, the rake is moved by a stepper motor until current balance is re-established within a given tolerance. Assuming the beam is axially symmetric (hypothesis that can be proved by the Faraday cup measurement) the shift of the rakes gives information about the beam centroid, that is the most accurate estimation of the thrust vector that can be derived by plume analysis.

Both types of plume diagnostics, shown in Fig. 4 as used during HET test campaign, are automatically driven by the facility/experiment computer control system which provides the motion of the rakes, the data acquisition and storage and the real time display of the measured parameters. Repeatability analysis of rakes positioning and alignment have been performed using a laser positioning system giving the following results: <math> < 0.3^\circ </math> for the Faraday cup rake, <math> < 0.2^\circ </math> for the tracking rakes. Accuracy and repeatability of the measurement carried out with the Faraday cup array was found to be within few percent as shown by the overlapping of three beam scans performed in the same thruster operating conditions with a time gap of 10 minutes between two successive readings (Fig. 5).

A typical plot produced by the thrust vector probe is shown on Fig. 6. In this case measurement accuracy strictly depends on the plume characteristics for each thruster. Expected value is about  $\pm 0.5^\circ$ .



**Fig. 5** Overlapping three successive beam scans in the same operating conditions of an HET proves the high repeatability of the beam current density distribution measured by the Faraday cup array.



**Fig. 6** Typical plot of the thrust vector tracking probes

The thrust stand, shown in Fig. 7, provides the mechanical, electrical and gaseous interface between the thruster and the facility.

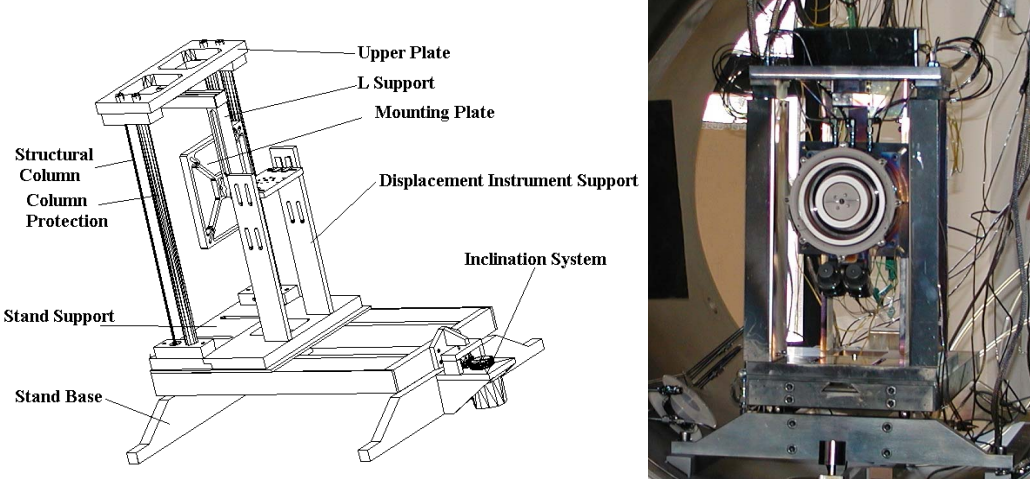


Fig. 7 Thrust balance overview

It mainly consists in an inverted pendulum configuration, in order to increase sensitivity (<1 mN), where the flexural elements are presented by four by stainless steel or Invar pipes. The thruster is installed on the movable part through a fine adjustable 4 DOF fixture for moving the centre of gravity on the structure. A non contact Linear Variable Displacement Transducer (LVDT) is used to measure the displacement of this movable part during thruster firing, with respect to the stiff fixed structure. The thrust measurement is obtained from the relative calibration curve. The sensitive element is mounted on a tilting platform whose pitch angle is accurately measured by an inclinometer (<0.01° deg resolution), and controlled by a stepper motor in order to perform periodical in-vacuum recalibration by using the weight component of the suspended mass to simulate thrust. The pitching system can also be used in order to validate the beam probe measurement system and check its directional accuracy.

The use of pipes as active elements allows to feed the propellant to the thruster and LN<sub>2</sub> to the thruster cooling system used to simulate in-space low temperature conditions (-80° C were reached at thruster mounting interface) without introducing additional stiffness. Finally the columns are protected by a three layer metal shield to prevent thrust stand thermal deformations and displacement due to differential heating caused by radiation or direct ion impingement. With this configuration an accuracy of better than 2% was achieved on the thrust measurement for a nominally 120 mN HET thruster.

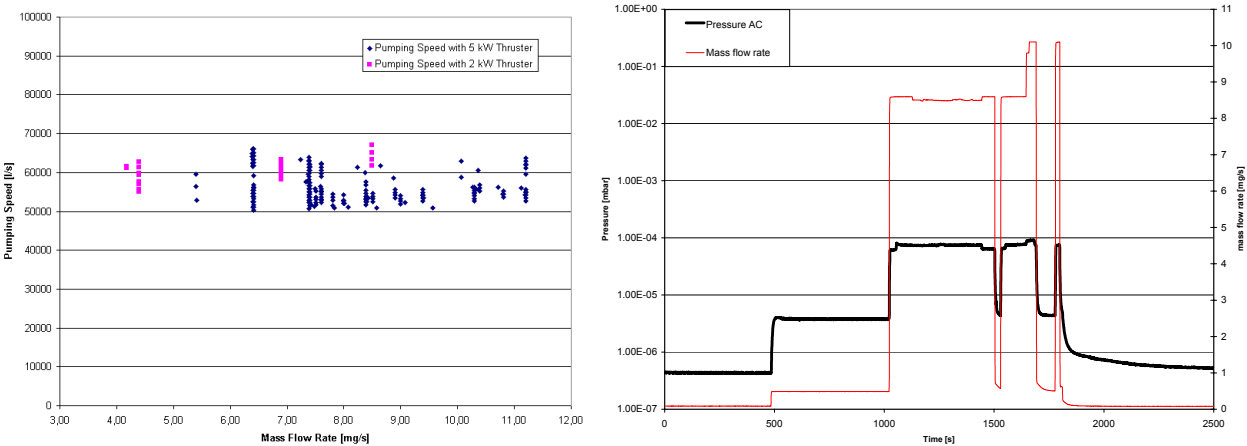


Fig. 8 Pumping speed at different mass flow rates for 2 and 5 kW thrusters (a) and typical pressure plot during firing at 2 kW for CHDs high capacity configurations (b)

4. IV-4 TEST FACILITY PERFORMANCE

Within Alta’s IV-4 test facility a 2 kW engineering model Hall effect thruster and a 5 kW laboratory model have been tested. The data regarding facility performance mainly confirm the expected performance thus

fully validating the facility design process. Pumping speed measured at different mass flow rates, during the tests of the two thrusters with CHDs in the high capacity mode, is shown in the following figure with the typical trend of pressure during a firing at 2kW.

Some long duration test cycles have been carried out allowing the monitored facility temperatures to reach a steady state value. In Fig. 9 cold head temperatures and conical target and ring temperatures during a 4-hour firing cycle at 2 kW are shown. No appreciable changes in chamber vacuum levels were observed.

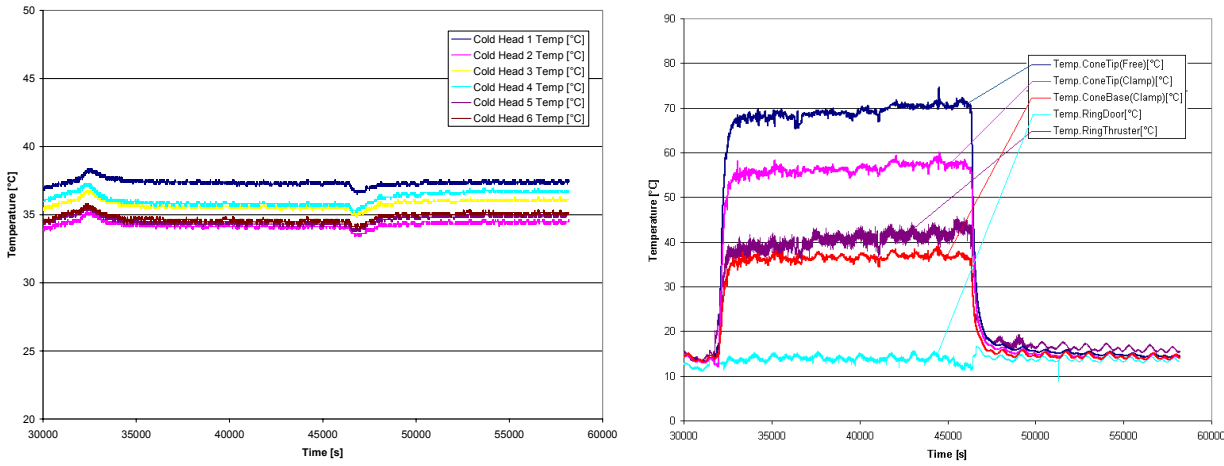


Fig. 9 Cold head, conical target and ring temperatures during a 4-hour firing cycle at 2 kW

**5. IPP TEST FACILITY DESCRIPTION**

The IPP test facility has been specifically designed to allow characterisation and life testing of EPS up to 25 kW, and for performance measurements and short duration experimental research on thrusters in the 25-50 kW range. In addition, propulsion integration and compatibility tests at the sub-system and system level may be easily performed thanks to the large free volume available ( $\approx 210\text{ m}^3$ ) and the large flexibility in its internal configuration.

The facility is composed of a large (5.7 m dia., 10 m length) AISI 316L stainless steel (with relative permeability  $\mu_r < 1.08$ ) cylindrical vacuum vessel and a lock chamber (AC, 2 m dia., 3.2 m length) connected to the main body through a large (1 m dia.) high-vacuum gate valve. A secondary service chamber (dia. >1 m) can be installed on one side of the main tank, while two smaller hatches (dia. >0.6 m) can be attached on the opposite sides of the primary lock chamber at  $\pm 13^\circ$  with respect to the axis of the main tank.

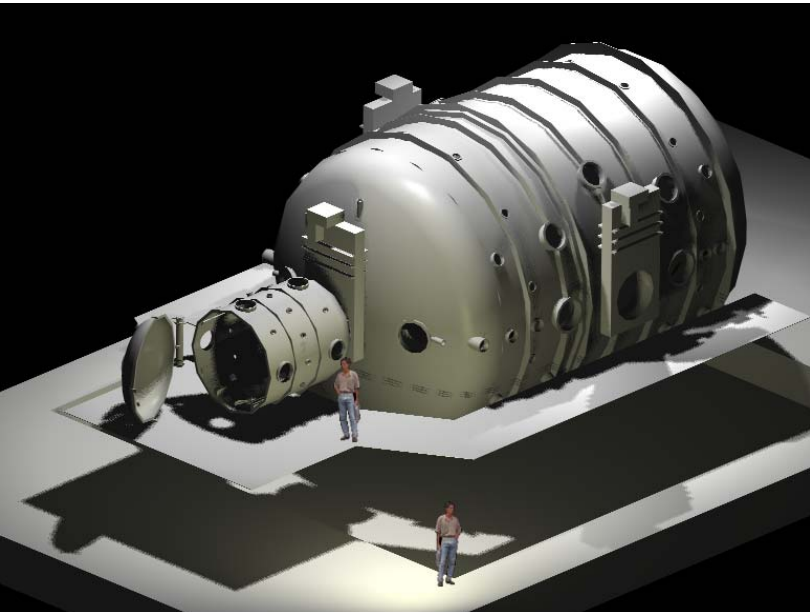


Fig. 10 External layout of the IPP test facility

The primary pumping system consists of 1 screw primary pump (250 m<sup>3</sup>/hr), 4 turbo-pumps (Varian VHT-2000) and 2 large cryopumps (Leybold Coolvac 5000), respectively for the low and high vacuum stages. The high speed pumping stage consists in a tailored configuration based on the results obtained with the IV-4 vacuum facility. In particular the inner surface of the main chamber is shielded with thermally controlled shrouds (5.4 m dia., composed by seven independent segments, which may be cooled by LN<sub>2</sub>, down to a temperature of 80 K), and initially contains about 15 m<sup>2</sup> of exposed cryo-pumping surfaces (maintained at a temperature below 50 K by 6 closed loop, gaseous helium, GHe, Gifford-McMahon cryo-generators). The nominal xenon pumping speed of this selected configuration will exceed 500,000 l/s, with the capability to install a further batch of panels (24 cold heads) for an expected maximum pumping speed up to 1,500,000 l/s [Xe].

In the design of the pumping cavity, featuring the double cone target already seen for the IV-4, simulation tools have been extensively used in order to optimise the pumping speed making a trade off between the characteristics of GITs and HETs. The results from PIC/DSMC codes show how the pumping system effectiveness can be increased by 35% with an optimised configuration of the cone with respect to the simple flat target passing from 371,000 l/s on Xe in this latter case to about 500,000 l/s.

Segmentation of the thermal shrouds, undergoing very different thermal loads depending on their position relatively to the thruster, helps in optimising the LN<sub>2</sub> consumption to limit the facility running costs especially for long duration tests. This segmentation together with the possibility of using heated gaseous nitrogen (GN<sub>2</sub>, to 380 K) allow a high flexibility of the vacuum chamber as system level thermal test site. A small solar simulator may also be installed on the side facing the main lock chamber.

In Fig. 13 the status of the facility on December 2002 is shown. The beginning of the preliminary operations are scheduled for mid-2003 once the subsystems (pumping system, LN<sub>2</sub> supply, Xe feeding lines, and beam diagnostics and control system etc.) will be accommodated in the facility.

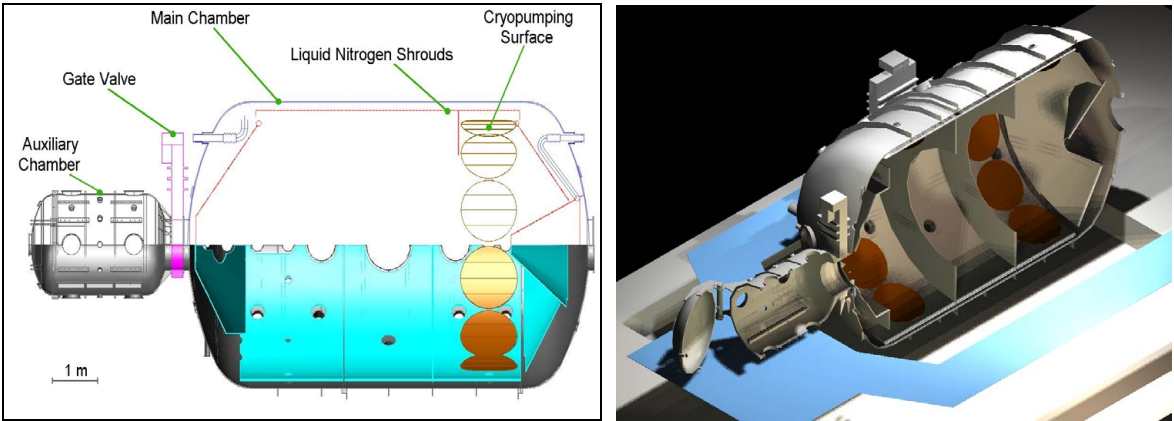


Fig. 11 IPP test facility: baseline configuration setup (left), maximum pumping setup (right)

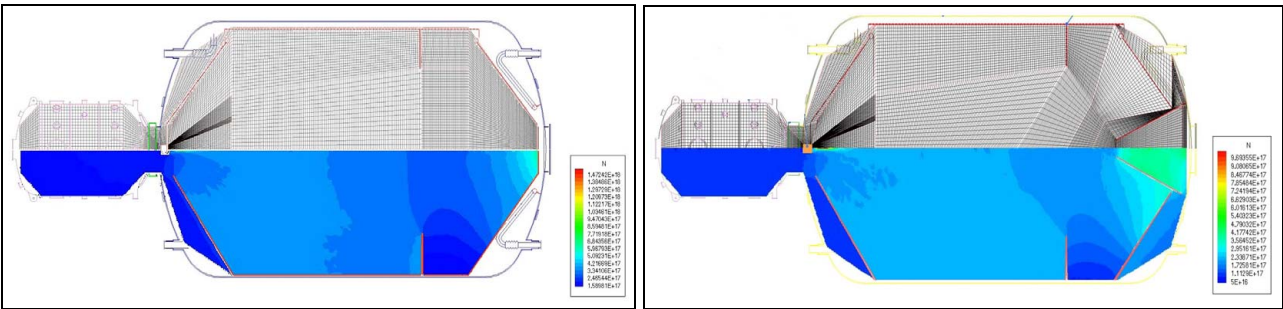


Fig. 12 Example of different simulated configurations: flat target (left), conical target (right)





**Fig. 13 IPP test facility during machining and assembly (December 2002)**

## **6. CONCLUSIONS**

The efforts undertaken by Centropazio-CPR/Alta during the past three years have finalized in the construction of two new vacuum facilities completely dedicated and specifically designed for medium and high power EPS testing including characterization, life test and acceptance phases. The design process based on the requirements for meaningful thruster characterization included the selection of proper material and configuration in order to minimise the interaction between the thruster and the surrounding environment. In particular the high speed pumping stage was tailored and optimised using non conventional shapes for the end target in order to maintain the specified pressure levels with large mass flow rates at an affordable running cost. To this purpose numerical analysis with DSMC codes were performed in order quantify the improvement in actual pumping speed. The tests with the pilot facility IV-4 using a 2 kW and a laboratory 5 kW Hall effect thrusters confirmed the expected results and performances for the facility and its diagnostics subsystems dedicated to EPS characterization. These results fully validated the design tools and gave good confidence for the technical choices adopted for the design and building of the IPP facility, the largest in Europe dedicated to EPS testing in the 10-50 kW class of power, scheduled to enter service in mid 2003.

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