Development of a 5kW Low-erosion Hall Effect Thruster

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Abstract: This paper reports on the development and experimental activities of a 5kW low-erosion Hall thruster designed and manufactured at SITAEL. The design of the thruster is based on the insights and experience obtained within the ESA-contract project "Long-Life, Low Erosion Hall Effect Thruster". The assessment of the ceramic walls erosion during and after a 250-hr endurance test shows a significant reduction with respect to conventional configurations. In addition, the data from the characterization test campaign and the endurance test indicate almost identical performance compared to SITAEL's 5kW Hall thruster of conventional magnetic field topology, with a maximum performance degradation of less than 3%. Due to its very low erosion and high efficiency characteristics, the newly-developed thruster has the potential to be used as the onboard propulsion system of long-lifetime missions.

I. Introduction

The interest towards the application of Hall thrusters for a wide variety of space mission scenarios has raised in the past years. Thanks to their versatility of operation, high efficiency and high power-to-thrust ratio, Hall thrusters can be considered as the most promising option for in-space electric propulsion.

A large number of theoretical, numerical and experimental efforts have been performed in order to increase the level of maturity of Hall thrusters and to meet the demanding requirements on efficiency and lifetime of future deep-space, GEO, and near-Earth missions. One of the areas of focus for these investigations is related to the erosion of the thruster acceleration channel, mainly due to the flux of energetic ions towards the walls near the channel exit. This phenomenon is the principal life-limiting factor for Hall devices having a conventional magnetic field topology. Consequently, the problem of channel erosion has to be properly addressed to use Hall thrusters in missions that require longer lifetimes with respect to what is currently achievable with standard-configurations.

A viable solution to the issue of ceramic wall erosion, known as "magnetic shielding", roots in the physical insight on Stationary Plasma Thrusters originally described by Alexey Morozov. In fact, as mentioned in Ref. 1, as the erosion

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progresses, the rate of wall erosion decreases in time and reaches an asymptotic value. Noting that in SPT-type Hall thruster the magnetic lines of force are almost equipotential lines, the recession of the channel outer and inner walls eventually results in magnetic lines becoming tangent to the walls near the thruster exit plane. This modification limits further progression of erosion by ion bombardment.

Accordingly, a number of researchers experimentally verified[2,3,4] that, in case the thruster channel is modified to imitate the end-of-life configuration and the magnetic field topology is redesigned, it is possible to inhibit erosion from the beginning of the thruster operational life. To achieve the magnetic-shielding of the ceramic channel, the walls are chamfered close to the exit plane and the magnetic field lines are reshaped in such a way that one field line (the so-called "grazing line") is tangent to the chamfer of the channel, and also penetrates into the near-anode region.

As described in Ref. 1, along magnetic lines $T_e = T_{e0} \cong const$ and $\phi = \phi_0 + T_{e0} \ln n/n_0$, where T_e, n and ϕ represent, respectively, the electron temperature, the plasma density and the electric potential and where the subscript 0 indicates the value at a reference point. Noting that close to the anode the electron temperature is lower, the magnetic field lines penetrating in this region can be considered as equipotential lines. In magnetically shielded configurations, the electric field is, thus, normal to the wall chamfer and repels the ions. Moreover, the lower electron temperature corresponding to the line tangent to the chamfer results in a lower electron flux to the wall and, therefore, to a lower sheath potential drop. Consequently, the ions reaching the walls acquire less energy in the sheath. These effects,

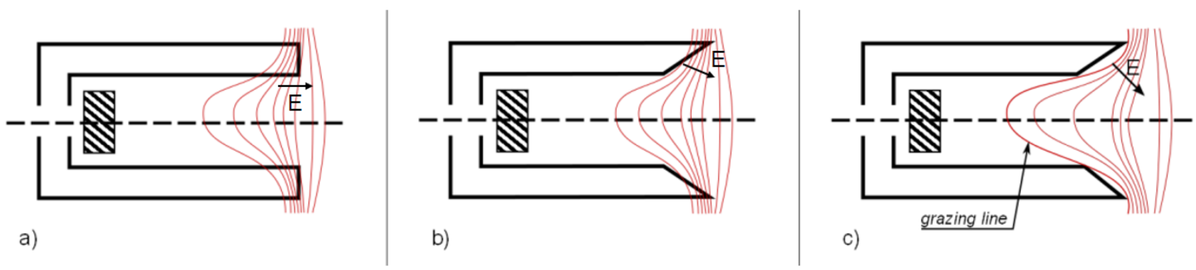

Figure 1. HT channel: a) standard configuration at BOL; b) standard configuration at EOL; c) magnetically-shielded configuration.

combined, significantly reduce the channel erosion (see Figure 1).

In the framework of the ESA contract N°4000113279/14/NL/KML "*Long-Life Long-Operation Hall Effect Thruster*" (LLHET), SITAEL has performed theoretical and experimental activities aimed at investigating the magnetic shielding scheme and at assessing its implications on lifetime and competitiveness of Hall thrusters. The overall objective of the project was to design, manufacture and test a low-erosion Hall thruster in order to increase the lifetime of current systems above 20 MNs. Applying the lessons learned from the functional test campaign[5,6] performed on a mock-up thruster, a new thruster with modified channel geometry and magnetic field topology was developed. This new thruster, named HT5k LL, is a 5kW-class Hall thruster designed to operate in the 2.5 to 7.5kW power range and with an estimated lifetime of above 50,000 hours. This paper reports the thruster performance evaluated during a characterization test and a 250-hr endurance test. A significant reduction of the channel erosion rate was confirmed by the data acquired from SITAEL's tele-microscopy system (AED).

II. Test Description

During the characterization and the short endurance tests, a number of diagnostics were used to assess the HT5k LL performance. Considering that a major test objective was to verify the effective elimination of wall erosion, the tele-microscopy system was implemented to periodically acquire images of the channel walls. Furthermore, being the design of the HT5k LL modified with respect to SITAEL's HT5k thruster, the characterization test was also aimed at confirming minimal performance degradation compared to the HT5k with conventional magnetic topology. Since the characterization campaign was performed using both externally and internally mounted cathodes, variations in performance due to the change in the cathode position were analyzed.

Through the 250-hour endurance test, the temporal variations of the thruster performance parameters were evaluated and the investigation of wall profiles using the AED system was performed. In order to minimize the effects of chamber background pressure in misreading performance data, the entire test campaign was performed in SITAEL's largest vacuum facility (IV10).

A. Overview of the HT5k LL design

The HT5k LL design is similar to that of the HT5k-M3 mock-up thruster developed within the framework of LLHET project[5]. However, some modifications (based on the outcomes of the HT5k-M3 functional test campaign) were made. In particular, as mentioned in Ref. 7 and observed in the functional tests[5], the cathode position considerably influences the thruster performance and the wall erosion symmetry. Consequently, it was decided to modify the design in order to allow for a centrally-mounted cathode.

In order to simplify the assembling of the thruster and mitigate issues concerning heat dissipation, the number of independent coils and their positions were changed. The magnetic circuit was modified to allow higher peak values of the magnetic field intensity in the acceleration region. The upgraded design prevents the saturation of the magnetic circuit over a wide range of coils currents, thus improving the thruster operation. Moreover, the number of mechanical parts constituting the thruster was greatly reduced.

Since pole erosion is a life-limiting factor in magnetically-shielded Hall thrusters, a shown in Figure 2, the external and internal magnetic poles are covered by ceramic parts. These parts are devised to protect the poles from high temperature electrons in the magnetic lens.

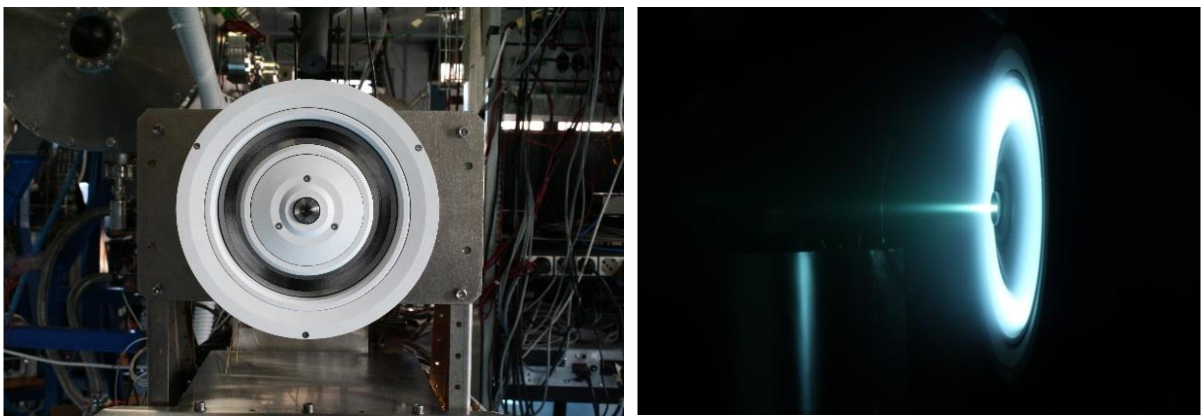

Figure 2. HT5k LL Thruster mounted on the thrust balance (left) and during operation (right)

B. Test Facility

As mentioned above, all tests on the HT5k LL thruster were performed in SITAEL's IV10 vacuum facility. SITAEL's IV10 vacuum facility is the largest vacuum chamber currently available in Europe for EP testing. The vacuum vessel has a total length of 9.4 m, an inner diameter of 5.7 m and a useful internal volume of 160 m^3.

The total pumping speed is of the order of 300000 l/s on xenon and ensures an ultimate vacuum pressure of less than 1×10^{-9} mbar and a chamber pressure less than 1×10^{-5} mbar during thruster operation with xenon. Figure 3 shows the chamber with its lid-cap open.

Figure 3. SITAEL's IV10 vacuum test facility

C. Erosion Diagnostics

As shown in Figure 4, in order to investigate the erosion phenomenon, the in-house Advanced EP Diagnostic (AED) system was used. The diagnostic system has been designed with the purpose of reconstructing the shape of a Hall thruster channel at different instants during its operational lifetime. Reconstruction of the channel shape is possible starting from a series of images of the channel walls acquired via high-precision camera at different times. A laser light is pointed at the insulator walls and sheds a bright line on them. When the ceramic material is eroded, the line projected by the laser on the walls changes its shape. By comparing images taken at different instants, it is possible to reconstruct the real profile of the insulator wall from the change in shape of the laser light projection. The diagnostic system can operate in the IV10 vacuum chamber. Since the whole system is mounted inside the vacuum facility, AED has an optimal view of the thruster and it can operate without opening the vacuum chamber. Furthermore, the system location allows avoiding any contamination due to the external environment when the erosion measurement is performed. During thruster operation, the surface of the camera viewport and the laser source are protected by a metallic shutter, which is opened only to perform the erosion measurements.

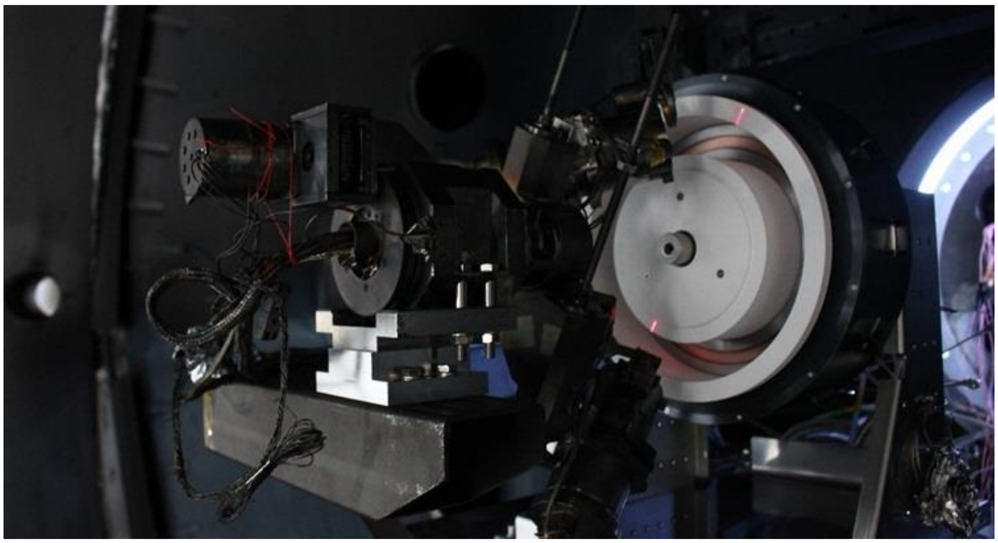

Figure 4. AED system (picture taken during the measurement of SITAEL's 20 kW Hall Thruster ceramic erosion).

D. Thrust stand and plume diagnostics

The HT5k performance and the thruster plume were characterized by means of the following diagnostic systems:

- A single-axis, double-pendulum thrust stand;
- A set of Faraday Probes.

The thrust produced by the HT5k LL in different operating conditions was measured by means of a dedicated thrust stand. The thrust stand is mounted on a tilting platform actuated by a stepper motor and it is capable of sustaining a thruster weight up to 15 kg. The sensing element is based on high-precision strain gauges. A calibrator is also added to check the proper functioning of the stand during the test.

Moreover, the characterization of the thruster plume in terms of plume divergence and ion current density distribution was performed. A set of Faraday probes mounted on a rotating circular rake with equal angular separations was used. Figure 5 shows the Faraday probes in parking position inside the IV10 vacuum chamber. The plume scans were periodically performed at each operating point during the short-duration endurance test.

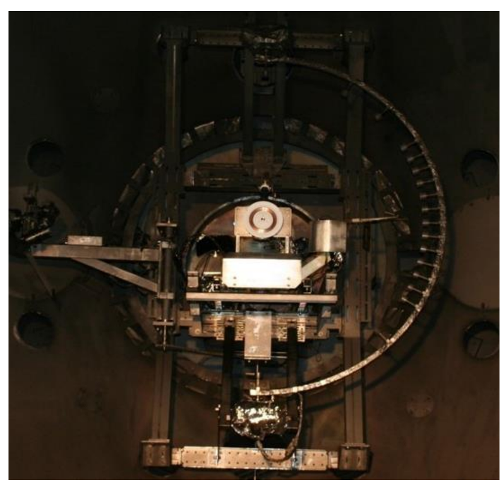

Figure 5. Faraday Probes diagnostic inside IV10.

III. Results

The extensive HT5k LL test campaign permitted the evaluation of the performance of the magnetically-shielded topology at several discharge voltages and both with the externally and the internally mounted cathodes.

The HT5k LL was extensively characterized using xenon before and after the 250 hours of endurance test. The characterization test was performed at different peak values of the magnetic field (16, 20 and 25mT), at discharge voltages between 250V and 500V and at discharge powers between 2.5 and 7.5kW. The HT5k LL operation was characterized with both the external and the central cathode.

The short endurance test was performed at 300V of discharge voltage, at 5kW of discharge power and using the externally-mounted cathode. Figure 6 shows the thruster during operation at its nominal operating condition.

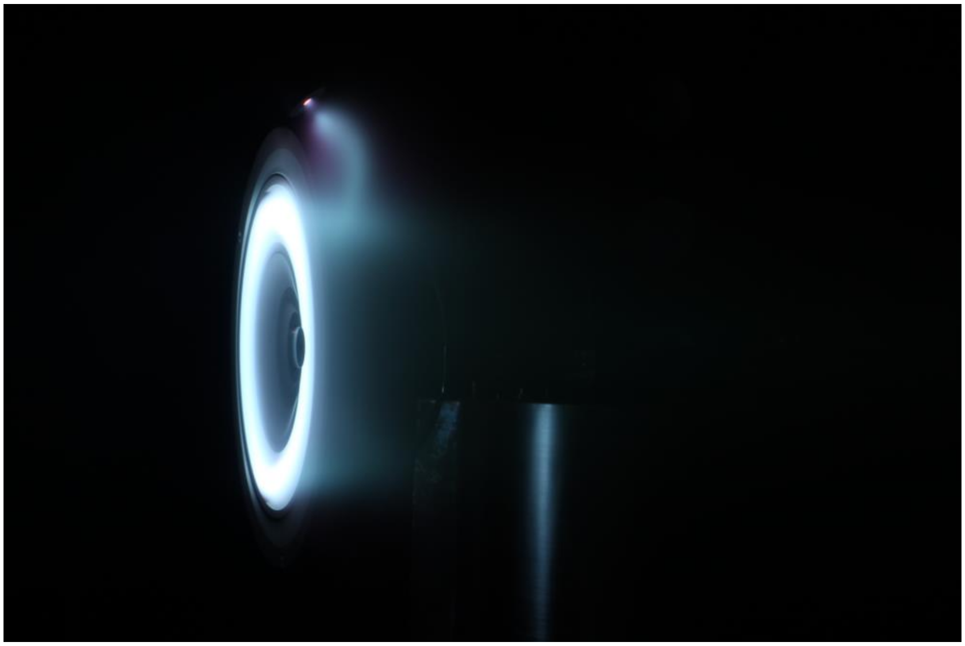

Figure 6. HT5k LL firing at 300V and 5kW with the external cathode during the endurance test.

E. HT5k LL Erosion Data

Figure 7 shows an example of the unprocessed images acquired by the AED system. These images correspond to the initial profiles at $\theta = 0°$ (corresponding to the cathode location) of the outer and inner channel walls. The resolution of adopted cameras is 2560x1920 pixels and the field of view spans an area of approximately 26x20 mm.

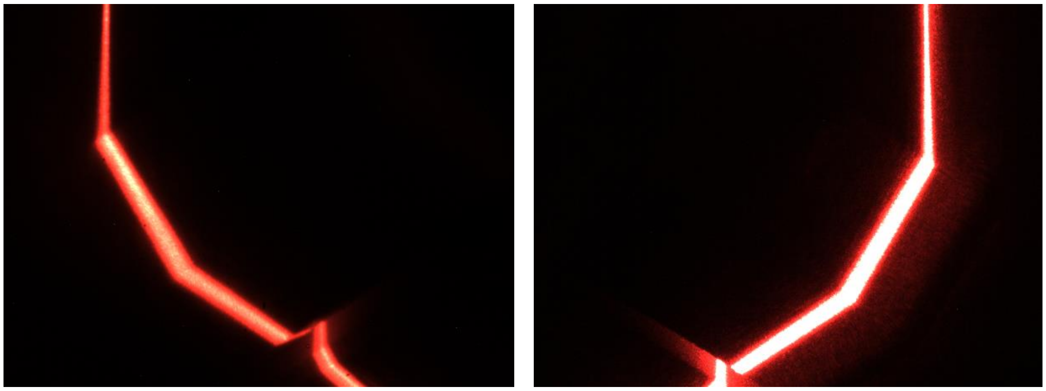

Figure 7. Outer channel wall (left) and inner (right) at the beginning of the tests.

After acquisition of each image, the reconstructed 3D solid shape is aligned with respect to previous acquisitions by means of an optimization procedure. The alignment procedure permits the comparison of reconstructed shapes at different times and, consequently, the assessment of channel erosion. The points of each profile are then mapped to the 3D space and converted to a cylindrical coordinates system (r, θ, z), aligned with the thruster axis. The plane z= 0 is arbitrarily set on the frontal edge of the ceramic walls at t = 0.

As shown in Figure 8, almost no variation in the channel inner wall profiles occurred at the end of the endurance test. Nevertheless, an azimuthal asymmetry in erosion (at about 120 degrees clockwise from the cathode position) is visible.

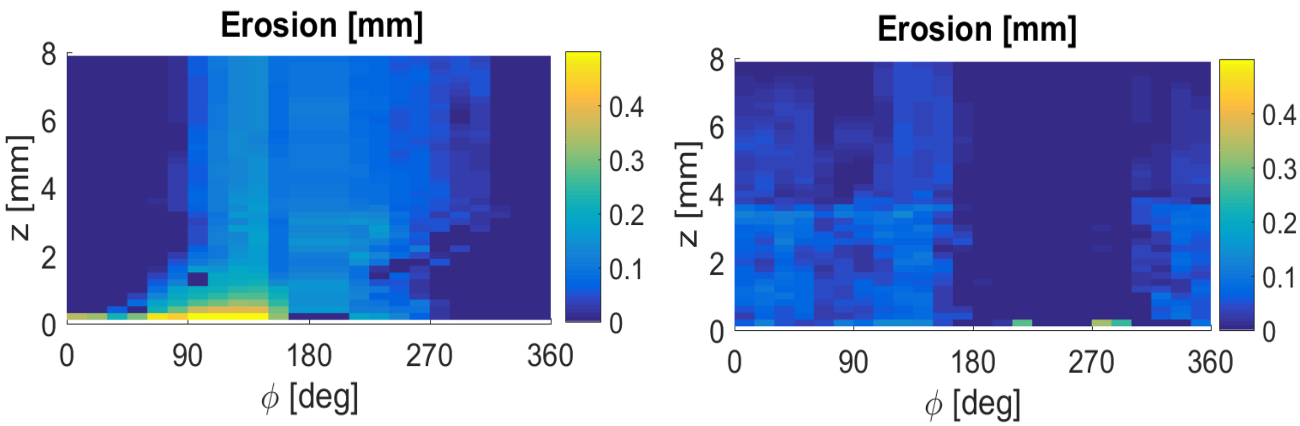

Figure 8. Erosion of the outer (left) and inner (right) ceramic walls.

The visual inspection of the ceramic at the end of the test campaign also reveals the success in implementing the magnetic shielding scheme. As shown in Figure 9, the inner wall is fully covered by back-sputtered deposition. On the contrary, a portion of the outer wall ceramic has remained white and slightly eroded, which is an indication of the azimuthal erosion asymmetry. This is probably due to the external cathode position. In particular, a peak of the erosion rate of 1-2 μm/hr was observed on the outer wall, near the exit section of the channel. Thruster operation using the internally-mounted cathode is expected to considerably mitigate this effect and reduce the erosion rate on the outer wall. However, the average erosion rate over the duration of the limited endurance test was less than 1 μm/hr, which is approximately one order of magnitude lower than that of the HT5k.

Figure 9. Post-test Inspection of the HT5k LL ceramic.

F. Performance Comparison between HT5k and HT5k LL

Modifying the conventional magnetic topology of Hall thrusters to implement magnetic shielding imposes, in principle, minor losses in terms of thruster performance. This point is both reported in the literature[2,8] and it was observed from the results of LLHET project test campaigns[5]. As a matter of fact, the decrease in performance can be minimized by means of an appropriate optimization of the magnetic topology and thruster design. The aim of the characterization test campaign was, in part, to verify this fact. Accordingly, Figure 10 shows the thrust vs. discharge power curves for HT5k and HT5k LL firings at discharge voltages of 300Vand 400V.

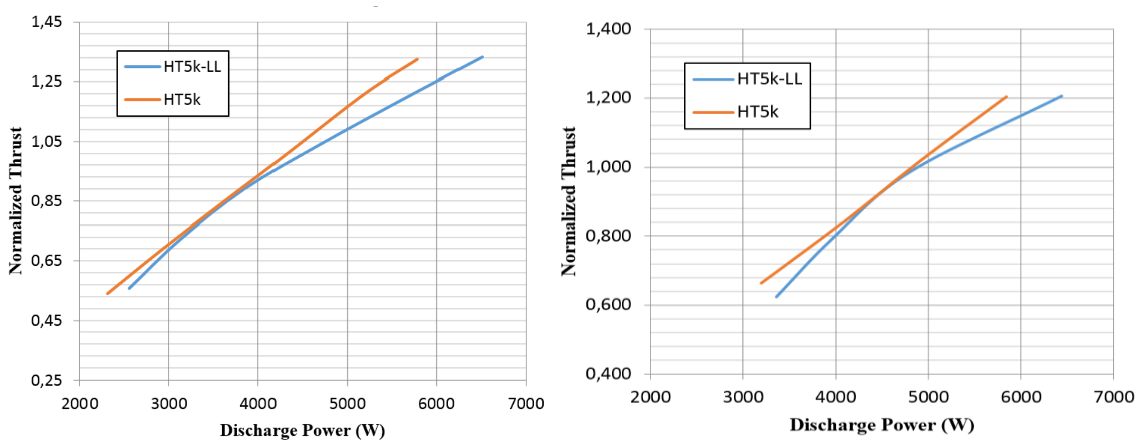

Figure 10. HT5k LL and HT5k: normalized thrust vs discharge power at 300V (left), and 400V (right) of discharge voltage.

Since the HT5k design is not compatible with a central cathode, the performance comparisons have been made with the HT5k LL firing with the external cathode. In particular, as seen in Figure 10, there is no substantial difference in the produced thrust near the nominal power level (i.e ~ 4.5kW).

In terms of the anodic efficiency, as shown in Figure 11, the trends between HT5k LL and HT5k at three different values of discharge voltage highlight almost identical performance, except at points relatively far from the thrusters' nominal operating point of 4.5kW of discharge power and 300V of discharge voltage.

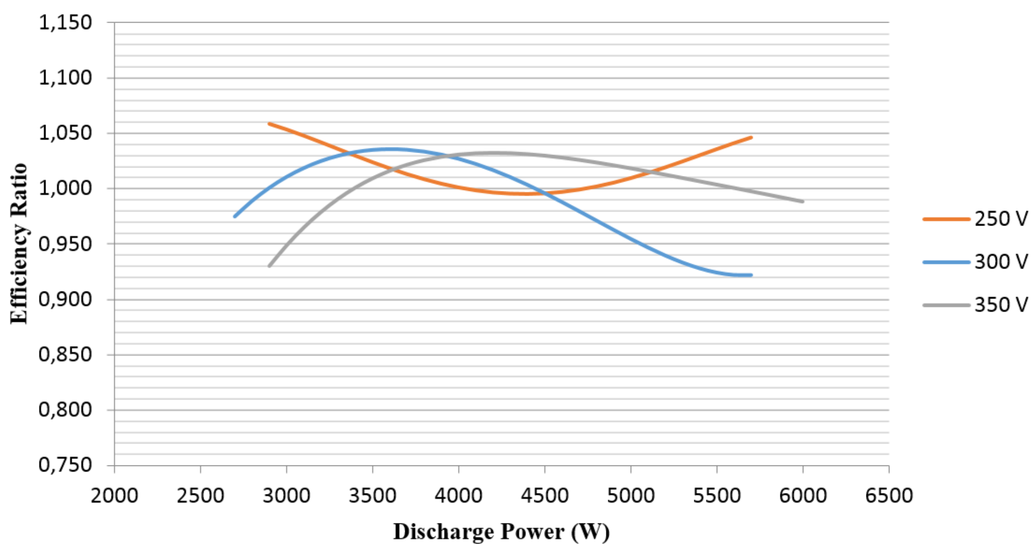

Figure 11. HT5k LL and HT5k: anodic efficiency ratio ($\eta_{HT5k\,LL}/\eta_{HT5k}$) versus discharge power at 250V, 300V and 350V of discharge voltage.

All in all, it is possible to conclude that the performance of the magnetically-shielded HT5k LL and the unshielded HT5k are relatively similar over a reasonably-wide range of operating conditions. Accordingly, the HT5k LL is capable of providing both high efficiency and considerably long lifetime. Since a centrally-mounted cathode is expected to reduce the ceramics erosion and to considerably improve the erosion symmetry, the HT5k LL was also characterized with the central cathode. The thruster showed (at discharge power levels of between 2.5 kW and 4 kW) anodic efficiencies up to 20% higher than those obtained at the same operating conditions with the external cathode.

G. HT5k LL Performance Comparison Before and After the Endurance Test

Another important aspect investigated as a part of the HT5k LL development plan is the characterization of possible temporal variations in performance of the thruster. The periodic measurements of thrust and plume divergence allowed studying the extent to which the performance varied through the endurance test. As it is clear in Figure 13, almost no variation in thruster performance during the endurance test at nominal operating point of 300V and 5kW is observed. In addition, Figure 12 shows the HT5k LL anodic efficiency, at 300 V, as measured during the post-endurance characterization test and compares it with the results obtained from the first characterization test. It can be noticed that the performance remained almost identical after 250 hours of firing.

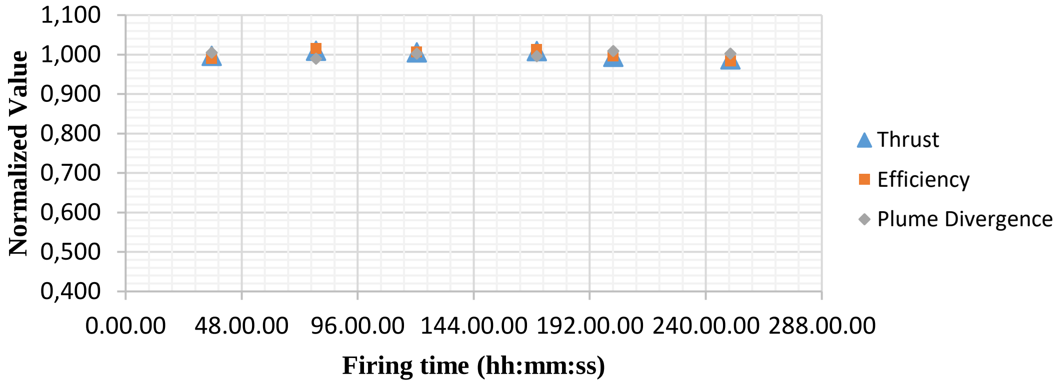

Figure 13. Endurance test: variations in thrust, anodic efficiency and plume divergence vs. hours of operation. The vertical axis is normalized with respect to the corresponding mean value.

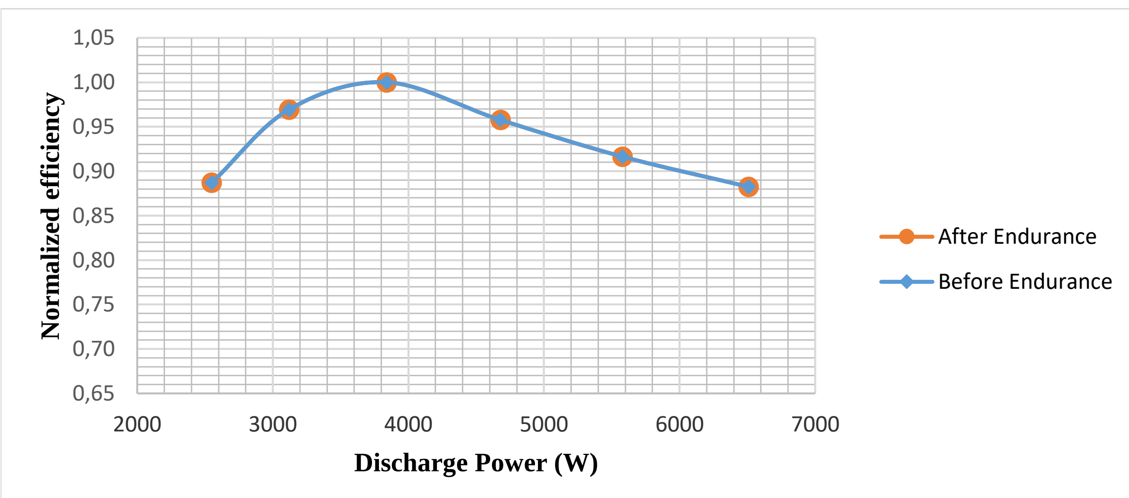

Figure 12. HT5K LL anodic efficiency: before and after the endurance test.

IV. Conclusions

In this paper, the results of the test campaigns performed on a newly-designed thruster, the HT5k LL, have been presented and discussed. The test campaigns proved the successful implementation of the magnetic shielding, reducing the erosion rate of the ceramic walls by approximately one order of magnitude with respect to conventional thrusters. Moreover, a limited degradation in performance compared to SITAEL's HT5k was observed. The high level of performance and low erosion are both great incentives behind investigating further aspects regarding the operation and design of the HT5k LL. The thruster will undergo further testing and design maturation during the course of ongoing projects.

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