

Theoretical and Experimental Investigation of Low-Erosion Hall Thruster Configurations

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Abstract: The ion acceleration in crossed electric and magnetic fields is the fundamental operating principle of Hall thrusters. Standard thruster configurations have annular channels with an almost radial magnetic field at the channel exit. The magnetic field hinders the electron flow in the axial direction but it does not impede the electron motion toward the walls, where a plasma sheath forms. This induces a flux of energetic ions to the walls and a significant degradation of the channel surfaces, which represents one of the main limiting factors to the lifetime of Hall thrusters. Since the magnetic field shapes the plasma properties inside the channel, the topology of the magnetic field can affect the erosion rate of the walls. For this reason, several non-standard magnetic configurations have been proposed in recent years that manage to substantially increase the lifetime of Hall thrusters. In the present paper, theoretical and experimental investigations performed on a 5kW-class Hall thruster with different magnetic field configurations are presented and discussed.

Nomenclature

β_H	=	Hall parameter
κ	=	Magnetic flux ratio parameter
λ	=	Magnetic flux function

I. Introduction

State of the art configurations of Hall thrusters are the result of a complex trade-off between thruster performance and reliability, in which the imposed magnetic field plays a significant role. The magnetic field acts as a barrier for the axial flow of electrons, decreasing the cross-field mobility by a factor $\sim 1/\beta_H^2$, where β_H represents the Hall

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parameter, i.e. the ratio between electron cyclotron frequency and collision frequency. In Hall thrusters typically $\beta_H \gg 1$ and the associated reduction of electron axial mobility allows for the generation of an electric field within the plasma. In particular, the voltage drop imposed between the cathode and the anode concentrates where the axial electron mobility is lower, i.e. in the region where the magnetic field reaches its highest value, giving rise to a large Hall current and accelerating the ions.

In the standard thruster configurations, the peak of the magnetic field is located near the exit of the ceramic channel. It is important to notice that the presence of the magnetic field breaks the plasma isotropy and, due to the low collisionality of the plasma, the electrons are free to flow along the magnetic field lines. The electrons in the region of the magnetic peak can thus reach the channel walls. Here, a plasma sheath forms in order to balance the flow of charged particles: the electron flow is reduced by the sheath electric field and by secondary electron emission (SEE), whereas ions are accelerated towards the walls. Among all the ions that flow through the sheath, those with energy above a specific threshold value, which depends on the wall material and on the impact angle, produce a sputtering of the wall.

The analysis of Hall thruster qualification campaigns and endurance tests has shown a substantial degradation of the ceramic channel walls. However, after an initial phase of high erosion rate, the wear process progressively reaches a saturation condition^{1,2}. This prompted the analysis of non-standard magnetic field configurations aimed at drastically increasing the thruster lifetime. The concept of magnetic shielding, investigated in Refs. 3 to 5, represents a promising approach to overcome the limitations of traditional thruster configurations.

In the present work, we analyze the influence of the magnetic field configuration on the plasma flow and on the thruster erosion. In Ref. 6, we introduced a quasi-2D model that allows for the simulation of complex magnetic configurations with simple computational tools. The model, based on magnetic coordinates that represent respectively the magnetic flux and the magnetic potential

$$\nabla \lambda = (\hat{\theta} \times \mathbf{B}), \quad \nabla \mu = \mathbf{B}, \quad (1)$$

has been adopted in the present work to perform numerical investigations of the plasma flow. The modelling results are then compared with the preliminary results of an experimental campaign carried out on the HT5k-M, a flexible 5 kW-class thruster prototype based on SITAEL's HT5k. More in details, in section II we present the HT5k-M and we analyze three non-standard magnetic configurations. In section III, we describe the model predictions for the performance and the plasma flow of the different HT5k-M configurations and we present the experimental results. Finally, section IV sums up the conclusions of the work, highlighting the main features of the performed investigations.

II. Thruster description and test setup

The HT5k is a high-power Hall thruster designed for operating with xenon in the 2.5 to 7.5 kW power range and especially intended for GEO and interplanetary applications⁷. The thruster, developed by SITAEL in the past years and extensively characterized, has an SPT-like configuration with a ceramic channel and an almost radial magnetic field that peaks at the channel exit. In 2015 the thruster performed a limited endurance test. It operated first with xenon and then with a mixture of krypton and xenon (see Ref. 8 for more details). The test highlighted a progression of the channel erosion in line with expectations and similar to that of thrusters of the same power level. Nevertheless, with the aim to extend significantly the thruster lifetime, different magnetic field configurations were designed and a new thruster prototype, the HT5k-M, was assembled. In order to assess the thruster performance and the wall erosion, as well as to validate the model of Ref. 6 against experimental data, a dedicated test setup and diagnostic system was developed. More in detail, measurements of near-wall and bulk plasma properties have been performed to gain an insight on the processes behind the wear of the ceramic channel. Following the approach of Refs 4, 9 and 10, flat tungsten probes were installed in the inner and outer ceramic walls of the HT5k-M. Moreover, in order to assess the plasma properties inside the channel, which is an essential step for model validation, fast scans of the plasma along the channel centerline were performed with a triple Langmuir probe.

A. HT5k-M Hall thruster

The HT5k-M is a thruster prototype, equipped with a flexible magnetic circuit and a chamfered channel. This thruster allows the characterization of a continuous spectrum of magnetic field configurations, ranging from standard topologies to completely magnetically shielded ones. In the framework of the present research, three configurations of the magnetic field have been identified (see figure 1). The main difference between the three configurations is in the position of the radial magnetic field peak with respect to the channel exit. To distinguish each configuration, we considered the magnetic line tangent to the channel chamfer, named grazing line in Ref. 3, and the one corresponding

to the peak of B_r on the centerline and we introduced the parameter $\kappa = \lambda_{grz}/\lambda_{peak}$. This parameter, which is similar to the parameter k introduced in Ref. 2, represents the fraction of the magnetic flux bounded by channel walls and enclosed between the anode and the magnetic field peak. Standard magnetic field configurations are characterized by $\kappa = 1$, whereas the magnetically shielded configuration of Ref. 3 has κ close to zero.

The first thruster configuration, named HT5k-M1, presents the same magnetic field topology of the HT5k, with the only difference of the chamfered channel, which simulates conditions close to the end-of-life of the thruster, $\kappa \cong 0.8$. In the second configuration, the HT5k-M2, the magnetic peak is moved further out of the channel, with $\kappa = 0.5$, in order to test intermediate conditions. Finally, the HT5k-M3 implements the magnetic shielding and, consequently, has $\kappa = 0$.

The operating condition of the thruster selected for the numerical investigation is at 300 V of applied voltage and 4.5 kW of discharge power. Both the HT5k and the HT5k-M are coupled with the HC20 cathode, a LaB6 high-current hollow cathode developed by SITAEL¹¹. For each configuration, the magnetic field peak along the channel centerline was of 20 mT.

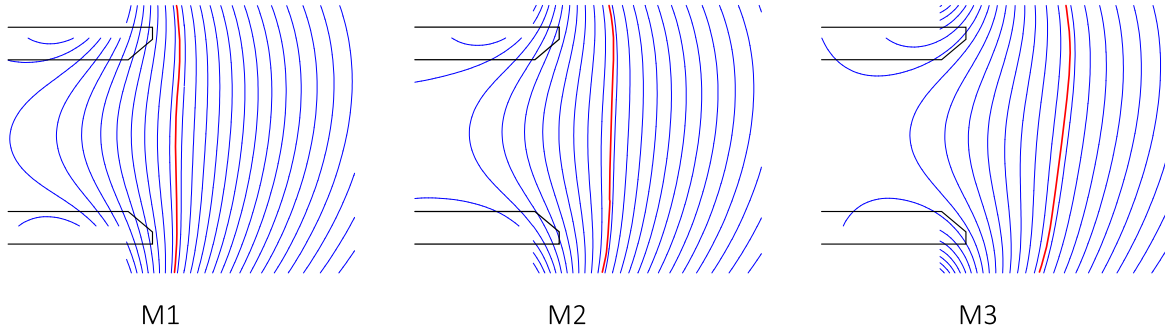


Figure 1. Investigated configurations of the HT5k-M thruster prototype. The red line indicates the magnetic field line corresponding to the peak of the magnetic field on the channel centerline.

B. Test setup

During a first test campaign carried out in SITAEL's IV4 vacuum facility, the diagnostic described in this section has been validated and calibrated. Moreover, the performances of the three HT5k-M magnetic configurations have been experimentally assessed.

Due to the higher vacuum level achievable with SITAEL's IV10 vacuum facility, a second test campaign has been carried out with the purpose of gathering more reliable data regarding the erosion and the performances of the M3 configuration. IV10 vacuum chamber, one of the largest currently available in Europe for electric propulsion testing, is specifically designed to reduce facility effects on thruster performance in terms of contamination, background pressure and electromagnetic effects due to chamber walls. Both facilities are equipped with Faraday probes allowing the characterization of the plume ion current distribution. Moreover, the same thrust stand, a single axis stand with a double pendulum configuration (see Ref. 7 for a detailed description), was used to assess the thrust generated by the HT5k and the HT5k-M. The different pumping capability and size of the two vacuum facilities introduces small differences in the evaluation of thruster performance. Due to the comparative approach of the performed campaign, the results presented in section III are expressed with respect to the reference configuration, i.e. the HT5k, operating in the more representative environment of IV10 vacuum facility.

The magnetic field generated by the HT5k-M has then been assessed using SITAEL's magnetic mapping tool, a three-axis robot with an integrated Hall probe. The measurements showed an almost axisymmetric magnetic field topology with a negligible azimuthal component and a good agreement with the 2D magnetic field simulation.

1. Flush-mounted wall probes

The near-wall plasma characteristics have been measured using flush mounted tungsten probes installed in the HT5k-M ceramic channel. Parietal probes have already been used successfully in the past^{4,9,10} to perform measurements of the local ion current density, electron temperature and plasma potential. The approach described in Ref. 10 is used to analyze the probe signals, accounting for the sheath expansion through the parametric model of Ref. 12. Uncertainties introduced by the sheath model introduce a significant error in the deduced plasma parameters, in particular for the plasma density. The error on the plasma density is estimated to be around 50%.

Four arrays of 1 mm diameter flat tungsten probes were flush mounted in the inner and outer diameters of the thruster's mock-up ceramic channel (see figure 2). Eight probes are installed in the outer wall (set A and C) and in the

inner wall (set B and D), as illustrated in figure 3(a). The probes were installed along the chamfer in the last 10% of the channel, where the maximum erosion was expected to occur. In order to compensate for azimuthal non-uniformities of the plasma properties, caused e.g. by the cathode position, sets A and C (as well as sets B and D) were placed 180 degrees apart from each other.

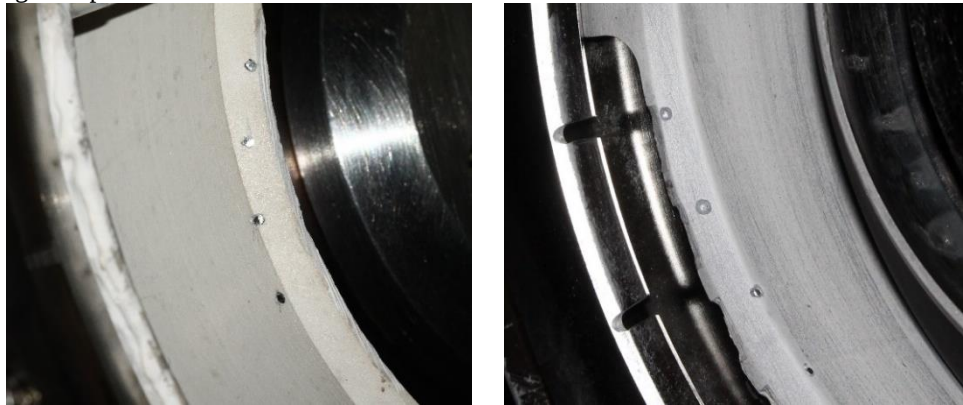


Figure 2. Pictures of the flush mounted wall probes.

A sketch of the axial distribution of the probes is illustrated in figure 3(b). Holes were machined inside the channel walls to allow for the installation of the probes. Each probe was connected to a copper wire inside the ceramic body. Grooves were manufactured in the ceramic walls in order to allow the passage of the copper wires throughout the thruster body and a high-temperature ceramic paste was used to hold the probe tips as well as to provide insulation for the copper wire along the ceramic body. Finally, alumina insulators were used to provide insulation for the copper wire near the back plate of the thruster.

Note that the three configurations of the HT5k-M shared the same ceramic channel and, consequently, the same probe arrangement.

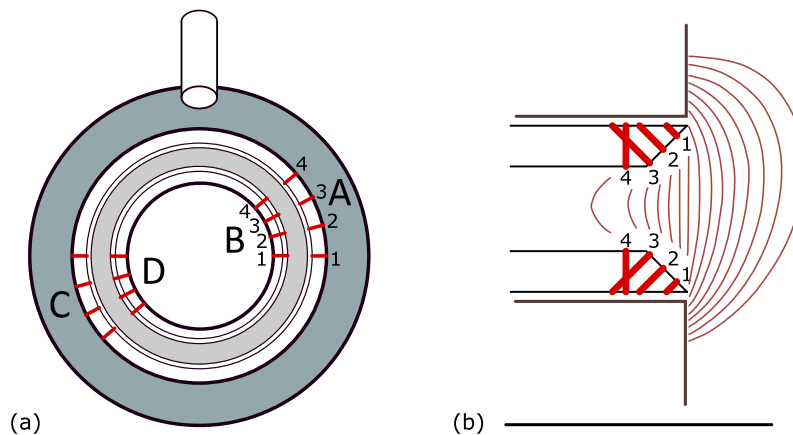


Figure 3. Schematic depiction of the distribution of the flush mounted wall probes.

2. Fast probe

A triple Langmuir probe mounted on an articulated arm (see figure 4) measured the electron temperature, plasma potential and density along the channel centerline. The arm rapidly inserts and extracts the probe from the thruster. The approach follows the one described in Ref. 4 and, since a triple Langmuir probe requires neither any voltage sweep, nor switching, it allows the assessment of the plasma properties within short times, of the order of the probe response time (see Ref. 13).

Three tungsten-rhenium wires (75% W and 25% Re) with a diameter of 0.178 mm were installed and bounded inside a 1/8-inch alumina tube. The electrodes were separated by a distance of ~ 2 mm in order to avoid any interaction and a length of 2 mm allowed having an adequate spatial resolution. The whole diagnostic system was designed to remain in a parking position, when not in use, in order to reduce the interference with the plasma plume and the deterioration of the triple probe. A high speed magnetic actuator allowed for a fast insertion of the probe inside the plasma (residence time in the high plasma density region lower than 0.2s) and an encoder was used in order to have

an accurate measurement of the probe position during the insertion. The design of the moving system has been performed in order to ensure a quasi-linear trajectory of the probe tip across the channel exit.

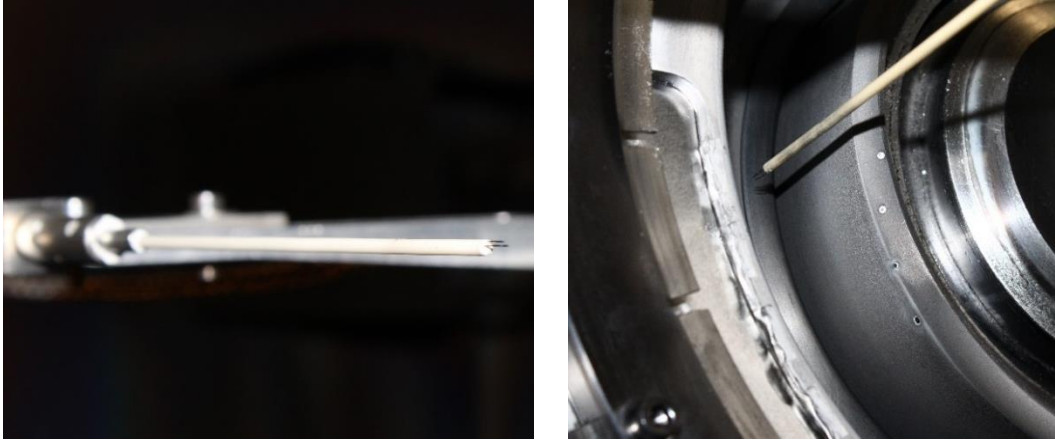


Figure 4. Pictures of the fast probe.

In order to convert the probe measurements to plasma properties (plasma density, electronic temperature and plasma potential), the parametrization described in Ref. 14 of the Laframboise solution for cylindrical Langmuir probes was implemented for the triple probe configuration. The Laframboise theory (see Ref. 15) was selected in order to take into account the expansion of the sheath with temperature, since the experimental conditions (particularly those in the zone of high electronic temperature at the channel exit) were outside the range of application of the thin sheath theory.

The measurements made during this experimental campaign had some particularities with respect to typical triple Langmuir probe measurements. The applied bias voltage was set to 0, 15 and 30 V in different tests to assess the effect of bias voltage on the measurements. Moreover, to compensate the asymmetry of the electrodes, due to the strong azimuthal Hall current that the probe intercepts, multiple probe acquisitions were performed with different electrode arrangements.

In order to infer the plasma properties, a Bayesian integrated data analysis¹⁶ was implemented using the code MultiNest¹⁷. As prior distributions for each parameter, wide constant priors were initially used for all the parameters along the analysis as a way to model the initial ignorance on the outcome of the inference. The likelihood of the data for the given model is quantified by means of a multivariate Gaussian function. The presence of gradients in the plasma properties sensed by the tip of each electrode was introduced in the analysis through the addition of nuisance parameters in the model. A marginalization of these parameters allowed calculating the distributions for each plasma property.

III. Comparison of simulations with plasma measurements

A validation of the model with the standard thruster configuration is presented in Refs. 6 and 18. The model successfully predicted the thruster performance at 5 kW of discharge power and, assuming the same Bohm parameter as the standard configuration, a comparative analysis of the three configurations working at the same power level was performed. The simulations estimated a performance loss of both the M2 and M3 configurations of approximately 6% of efficiency and a significant reduction of the wall erosion in the M3 configuration.

In order to investigate the influence on the plasma flow of the magnetic field configuration, two separate and consecutive test campaigns were planned and performed. Preliminary results of the experimental campaigns are summarized in this section together with numerical simulations of the plasma properties. For each of the three configurations described in section II, the anomalous diffusion parameter was calibrated using experimental data.

1. Numerical results

The plasma properties calculated for the HT5k-M1 and the HT5k-M3 configurations are shown in figure 5. In the M3 configuration, for which the acceleration region is moved outside of the channel, the electron temperature is not limited by the interaction with the ceramic walls and it is free to reach very high values. The high electron temperature implies faster plasma diffusion and higher plume divergence, which are only partially compensated by the focusing of the magnetic field lines. Moreover, the higher electron temperature causes a rapid ionization of the propellant,

before the acceleration region, which implies a more effective utilization of the applied potential and, since the plasma particles are rapidly accelerated, a lower plasma density in the near plume region.

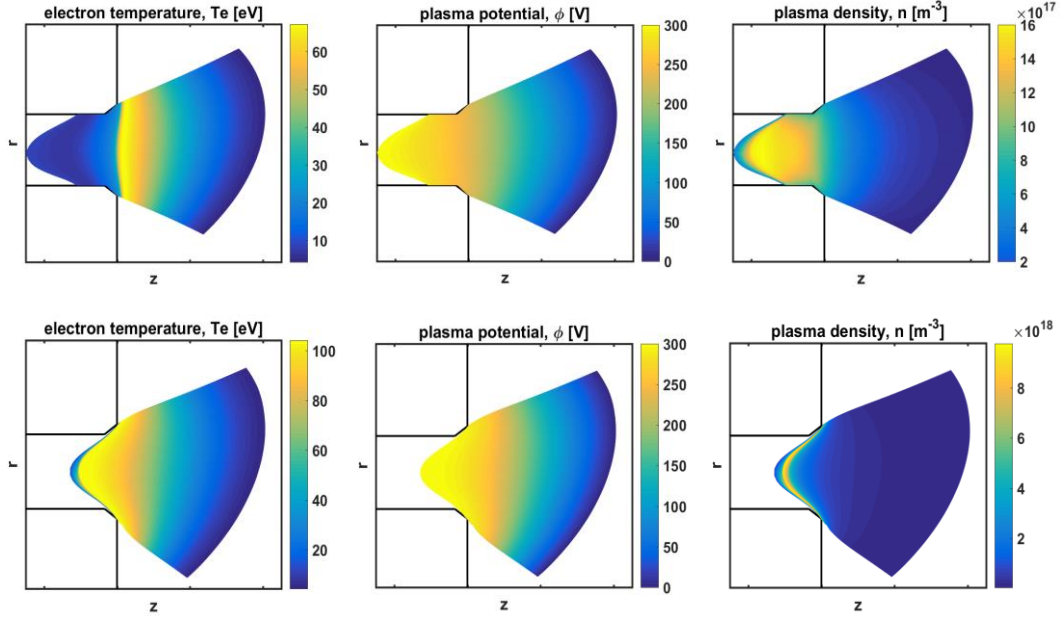


Figure 5. Simulation results for the electron temperature, plasma potential and plasma density of the M1 (top) and M3 (bottom) configurations.

2. Thruster performance

Based on the prediction of the plasma properties at the cathode section, the model allowed estimating the thruster performance. Table 1 presents the results of the experimental campaign in terms of performance together with the corresponding simulation values, showing small differences between the model predictions and the experimental data. The model slightly overestimates the thruster performance, probably due to the simplifications introduced in the description of the anode and far-plume regions. The comparison between the different HT5k-M configurations shows that no significant degradation of the performance can be observed in the M3 configuration, whereas a clear degradation of the performance was assessed, both numerically and from the experiments, in the M2 configuration. Since the model investigates only the near plume region, it is difficult to directly compare the simulations with the measurements of plume divergence, calculated as the half angle that contains 95% of ion flow. Nonetheless, it can be noticed that using a shielded configuration implies an increase of the plume divergence. However, this increase seems comparable with that of the thruster end-of-life condition.

	Mass flow rate $\dot{m}$ [mg/s]	Discharge Power P_d [W]	Thrust T [mN]	Specific impulse I_{sp} [s]	Thrust efficiency η [%]	Plume divergence θ_{95} [deg]
HT5k	15.0 ± 0.1	4425 ± 33	263 ± 5 (269)	1790 ± 50 (1826)	0.52 ± 2.5 (0.54)	37 ± 0.1
HT5k-M1	14.1 ± 0.1	4400 ± 33	255 ± 5 (259)	1840 ± 50 (1871)	0.52 ± 2.5 (0.54)	46 ± 0.1
HT5k-M2	13.3 ± 0.1	4550 ± 33	237 ± 5 (251)	1830 ± 50 (1820)	0.47 ± 2.5 (0.49)	55 ± 0.1
HT5k-M3	13.9 ± 0.1	4525 ± 33	257 ± 5 (260)	1870 ± 50 (1924)	0.52 ± 2.5 (0.55)	46 ± 0.1

^a For all configurations the applied voltage is 300 V.

^b Simulation results are reported in brackets.

Table 1. Performance of all thruster configurations^{a,b}.

3. Plasma properties

The measurements performed with the wall probes are reported in figure 6. The near wall plasma properties are shown for the M1 and M3 configurations, averaged with respect to the two azimuthal probe sets, both for the inner and outer walls. In agreement with the magnetic shielding approach, the translation of the magnetic field peak outside of the channel corresponds to a decrease of the electron temperature near the walls. In particular, the electron temperature of the HT5k-M3 configuration is below 10 eV at the walls. Such low temperatures, in a region where instead the plasma potential is high and close to the applied voltage, imply low ion energies in the near wall region and, consequently, low sputtering. Indeed, since the acceleration process is not started and the potential drop in the sheath is low, the energy of the ions that impact on the wall is below the sputtering threshold (a clear description of the erosion process is presented in Ref. 4).

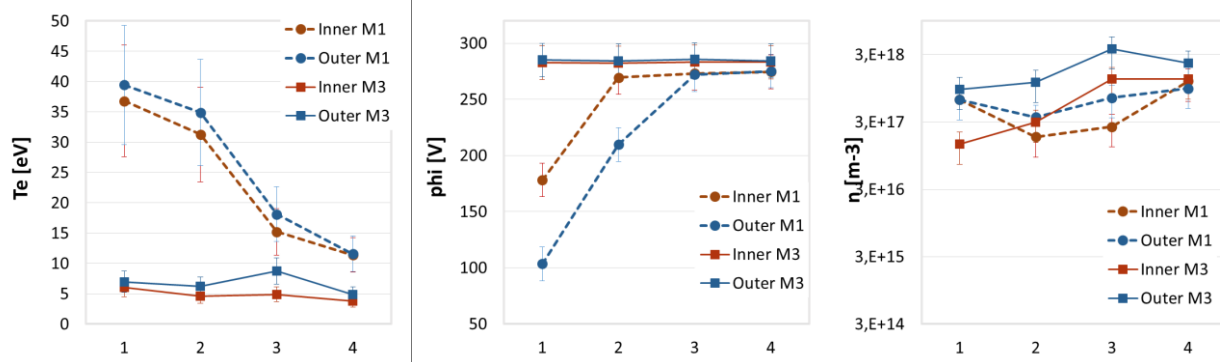


Figure 6. Plasma properties obtained from wall probe measurements for M1 and M3 configurations.

As shown in figure 7, another confirmation of this conclusion was given by the post-test inspection of the M3 configuration that showed a significant deposition on the walls of graphite particles, which are produced by the sputtering of the vacuum facility protective layers due to the thruster plume impingement. The presence of back-sputtered material on the channel walls is a clear indication of low erosion rates, since the rate of graphite deposition is typically below $10^{-2} \mu\text{m/h}$, whereas the maximum erosion rate of the HT5k at the beginning of life is $\sim 10 \mu\text{m/h}$.

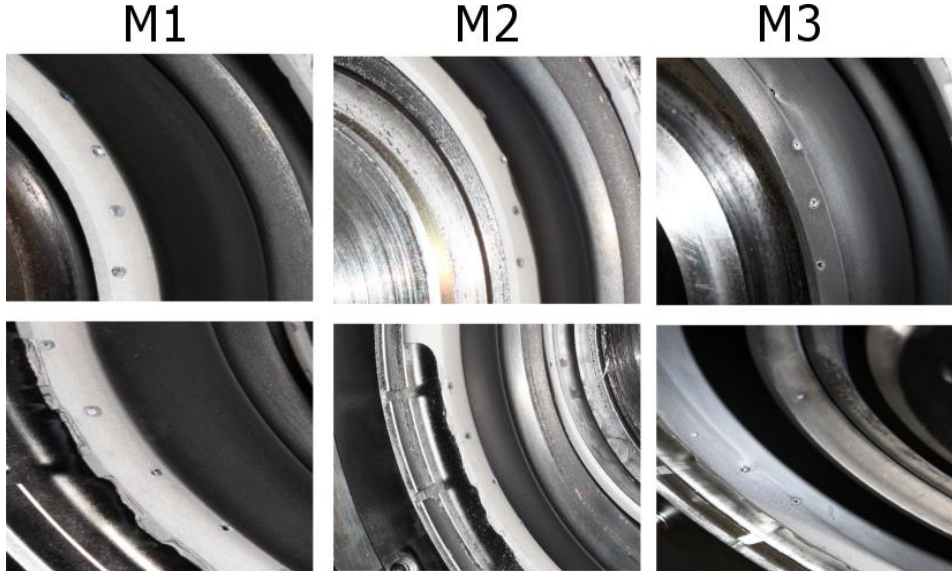


Figure 7. Pictures of the inner (above) and outer (below) walls after the firing test for M1, M2 and M3 configurations.

An asymmetry between the inner and outer wall is observed, which corresponds to the different electron temperatures that can be observed in the performed measurements (see figure 6). A similar behavior was observed during long endurance tests of thrusters with traditional configurations (see Ref. 8).

Finally, the measurements performed with fast Langmuir probe (see figure 8) for the configurations M1 and M3 are illustrated in figure 9. On the horizontal axis it is reported the axial position of the probe with respect to the channel

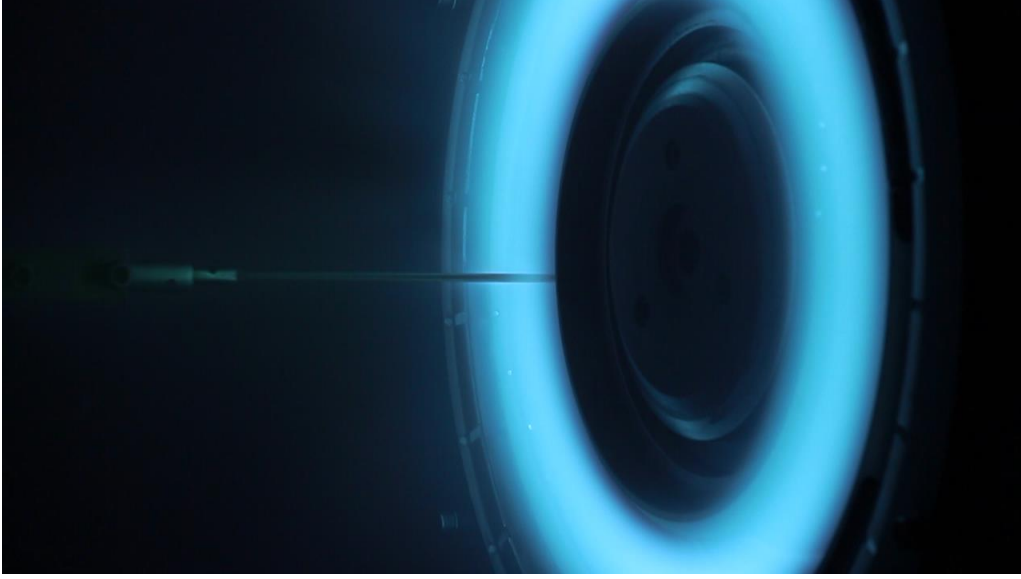


Figure 8. Pictures of the fast probe performing a measurement inside the channel of HT5k.

exit section, whereas the color map corresponds to the probability that a given value represents the measured plasma property and the red line represents the parameter value with the highest probability. Due to the relatively low voltage applied between the electrodes of the triple Langmuir probe, a limit imposed by the setup, we obtained an accurate description of the plasma flow only in the regions with electronic temperatures below ~ 15 eV. It is however possible to assess, from the comparison of figures, that higher electron temperatures are measured in the M3 configuration, in line with the simulation results. Moreover, in this configuration the region of high temperature extends outside the channel for a longer fraction of the probe trajectory. Notice that the magnetic field grazing line intercepts the probe trajectory at approximately $z = -10$ mm, where the measured temperature is compatible with the value obtained by the wall probes. Hence, even if the region of high temperature enters inside the channel, the magnetic configuration allows shielding the channel walls.

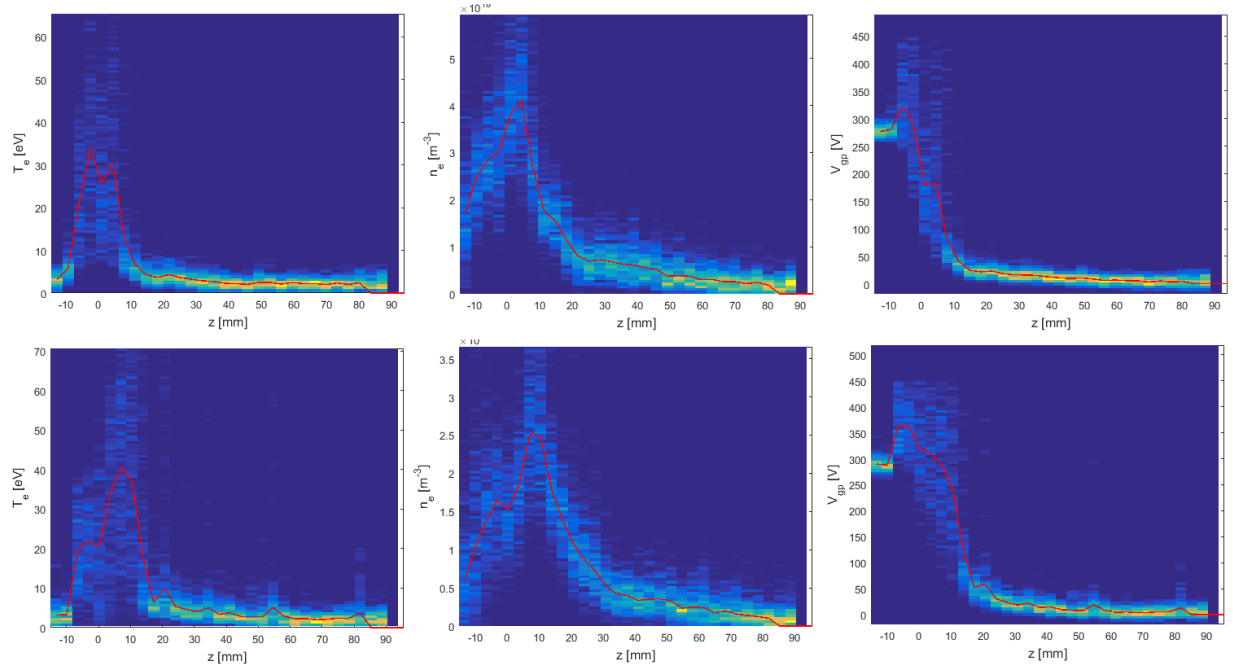


Figure 9. Electron temperature, plasma potential and plasma density for the M1 (top) and M3 (bottom) configurations, measured along the channel centreline with the triple Langmuir probe.

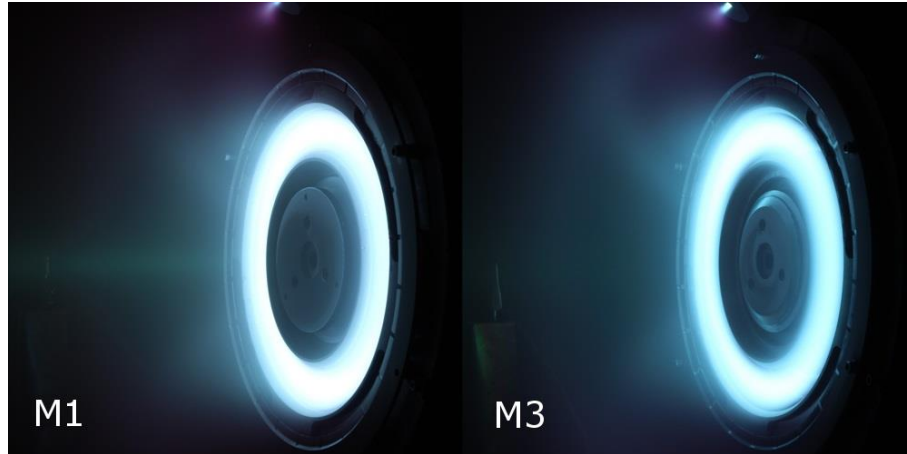


Figure 10. Pictures of the HT5k-M during the functional test campaign of the M1 (left) and M3 (right) configurations.

IV. Conclusion

The purpose of the present work was to evaluate the effect of different magnetic configurations on the performance and erosion of a Hall thruster. In order to achieve this objective, a flexible thruster prototype was developed and manufactured at SITAEL, based on the HT5k thruster. Then, theoretical and experimental investigations were carried out, focusing in particular on the effectiveness of the magnetic shielding approach. Three different magnetic configurations, with a progressively increasing shielding, were designed and tested. The model developed in Ref. 6, based on magnetic coordinates, was adopted to simulate the plasma flow of the three configurations and to evaluate the performance. The model was validated against the experimental measurement showing a remarkable agreement between experiments and prediction, confirming the validity of the modelling approach. From the experimental point of view, the influence of the magnetic field configuration on the plasma flow was assessed in a complex experimental campaign, for which an ad-hoc diagnostic setup was designed and integrated in the thruster (wall Langmuir probes) and inside the vacuum chamber (fast triple Langmuir probe). For each configuration, data acquisitions with the wall probes and fast Langmuir probe were performed together with thrust and plume measurements. The performance results of the magnetically shielded configuration highlighted a minor decrease of the thrust, with respect to the HT5k, without significant effects on the thrust efficiency. The measurements performed with the wall probes, at the end of ceramic channel, showed instead a significant reduction of the electron temperature and a potential profile compatible with the translation of the acceleration region outside of the channel (see figure 10). These results were confirmed by the measurements performed with the fast Langmuir probe. Moreover, the scan of the plasma properties along the channel centerline showed an increase of the electron temperature for the magnetically shielded configuration. Finally, the analysis of the wall measurements confirmed a substantial reduction of wall sputtering. This is in accordance with results of the investigations performed in Ref. 3 and confirms the effectiveness of the magnetic shielding approach.

Acknowledgments

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References

- ¹Mikellides I. G., Katz I., Hofer R. R., Goebel D. M., de Grys K. and Mathers A., “Magnetic shielding of the channel walls in a Hall plasma accelerator”, 2011 *Phys. Plasmas* Vol. **18** 033501.
- ²Mitrofanova O. A. and Gnizdor R. Y., Influence of SPT magnetic field on life time characteristics of the thruster”, 2013 *Proc. 33rd Int. Electric Propulsion Conf. (October 6 – 10, 2013, Washington D.C., USA)* Paper IEPC-2013-051.

- ³Mikellides I. G., Katz I., Hofer R. R. and Goebel D. M., “Magnetic shielding of a laboratory Hall thruster. I. Theory and validation”, 2014 *J. Appl. Phys.* **115** 043303.
- ⁴Hofer R. R., Goebel D. M., Mikellides I. G. and Katz I., “Magnetic shielding of a laboratory Hall thruster. II. Experiments”, 2014 *J. Appl. Phys.* **115** 043304.
- ⁵Grimaud L., Mazzoufre S., “Ion behavior in low-power magnetically shielded and unshielded Hall thrusters”, 2017 *Plasma Sources Sci. Technol.* **26** 055020.
- ⁶Andreussi T., Giannetti V., Leporini A., Saravia M. M. and Andrenucci M., “Influence of the magnetic field configuration on the plasma flow in Hall thrusters”, *Plasma Phys. Control. Fusion* (to be published)
- ⁷Ducci C., Arkhipov A. and Andrenucci M., “Development and performance characterization of a 5 kW class Hall-Effect thruster”, 2015 *Proc. 34th Int. Electric Propulsion Conf. (July 4-10, 2015, Kobe, Japan)* Paper IEPC-2015-215.
- ⁸Andreussi T., Giannetti V., Leporini A., Estublier D., Edwards C., Rossodivita A. and Andrenucci M., “Temporal evolution of the performance and channel erosion of a 5kw-class Hall effect thruster operating with alternative propellants” 2016 *Proc. 5th Space Propulsion Conf. (May 2-6, 2016, Rome, Italy)* Paper SP2016-3125164.
- ⁹Kim V., Kozlov V. I., Skrylnikov A. I., Umnitsin L. N., Svotina. V. V., Bouchoule A. and Prioul M., “Investigation of the Local Plasma Parameter Distributions in the SPT Accelerating Channel Under Increased Discharge Voltages”, 2005, *Proc. 29th Int. Electric Propulsion Conf. (New Jersey, USA)* Paper IEPC-2005-004.
- ¹⁰Shastri R., Gallimore A. D. and Hofer R. R., “Near-Wall Plasma Characterization of a 6-kW Hall Thruster”, 2009 *Proc. 31st Int. Electric Propulsion Conf. (September 20-24, 2009, Michigan, USA)* Paper IEPC-2009-133.
- ¹¹Pedrini D., Albertoni R., Paganucci F. and Andrenucci M., “Theoretical Model of a Lanthanum Hexaboride Hollow Cathode”, 2015 *IEEE Trans. Plasma Sci.* **43** p. 209-217.
- ¹²Sheridan T. E., “How big is a small Langmuir probe?”, 2000 *Phys. Plasmas* **7** 3084.
- ¹³Chen A. and Sekiguchi T., “Instantaneous Direct-Display System of Plasma Parameters by Means of Triple Probe”, 1965 *J. Appl. Phys.* **36** 2362.
- ¹⁴Mausbach M., “Parametrization of Laframboise’s results for spherical and cylindrical Langmuir probes”, 1997 *J. Vac. Sci. Technol. A* **15** 2923.
- ¹⁵Laframboise J. G., “Theory of spherical and cylindrical langmuir probes in a collisionless, maxwellian plasma at rest”, 1966 *University of Toronto Institute for Aerospace Studies Report* **100**.
- ¹⁶Ford, O., “Tokamak Plasma Analysis through Bayesian Diagnostic Modelling” Ph.D. Dissertation, Imperial College London, London, UK, 2010.
- ¹⁷Feroz F., Hobson M. P. and Bridges M., “MULTINEST: an efficient and robust Bayesian inference tool for cosmology and particle physics”, 2009 *Mon. Not. Roy. Astron. Soc.* **398** 1601.
- ¹⁸Giannetti V., Andreussi T., Leporini A., Estublier D. and Andrenucci M., “Long-Life Low Erosion Hall Effect Thruster: Model and Simulations”, 2016 *Proc. 5th Space Propulsion Conf. (May 2-6, 2016, Rome, Italy)* Paper SP2016-3125199.