

Design and first test campaign results with a new flexible magnetic circuit for a Hall thruster

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In a Hall thruster, the magnetic field at the origin of the electron confinement is established through an assembly composed of coils or magnets and a magnetic circuit to guide the flux. The standard magnetic architecture, however, suffers from a lack of flexibility as its main purpose is to generate a selected topology that warrants a high and stable performance level. This contribution reports on a new magnetic circuit, which permits to vary the magnetic field over a vast range of configurations. Compared with conventional magnetic circuit used in Hall Thrusters, the proposed circuit has been especially designed to control in an independent manner the characteristics of the magnetic topology in terms of position, gradients, intensity, width and so on. The design and operation of the new magnetic assembly is first presented together with the possibilities it offers illustrated with magnetic configuration examples. In a second part, results obtained during a measurements campaign carried out in a Snecma test chamber at Vernon in France are presented. The new magnetic structure has been mounted in a thruster prototype based on the PPS®1350 architecture. The prototype, named PPS-Flex, has been successfully fired with xenon. The thrust and the ion beam divergence have been determined for several magnetic topologies.

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I. Introduction

Hall thrusters (HTs) are plasma thrusters used on board telecommunication satellites for propulsion tasks mainly for geostationary station keeping. Unlike ion engines, no accelerating grid is used in a HT. The electric field penetrates inside the plasma discharge by reducing the electron conductivity with the help of a transverse magnetic field. An annular geometry is used to create a closed-electron drift in the $E \times B$ direction, the so-called Hall current. The drift increases of the residence time of the electrons inside the channel, which leads to an efficient ionization of the propellant gas. The channel, wherein the discharge is produced, is made with ceramic walls to in order to isolate the plasma from the magnetic circuit. The anode, located at the back of the channel, serves also as a gas distributor. The cathode, located outside the channel, provides primary electrons to initiate the discharge as well as electron to neutralize the ion beam [1], [2].

The magnetic structure of a conventional HT is composed of a magnetic circuit with two poles pieces and one internal coil and four external coils. Magnetic screens can be added if necessary. Along the channel centerline, the axial magnetic field gradient is positive inside the thruster channel and negative outside when following the ion flow direction. The configuration of the magnetic circuit permits to locate the magnetic field maximum strength in the exit plane. The magnetic field lines have a concave shape. The magnetic lens is approximately symmetrical about the channel axis. The role of the magnetic field is crucial since it permits to trap the electrons long enough inside the HT channel to be able to ionize efficiently of the neutral flow. Moreover, the magnetic field shape plays a role for the ion focusing. In an ideal situation where the potential drop along the magnetic field lines is small, the magnetic field lines are almost equipotential. By changing the magnetic field topology, the electric field profile can be changed to focus the ion trajectories towards the thrust axis (and far from the walls). In the real situation, the electric field lines deviates from the magnetic field lines and the control of the ion beam focusing requires an optimized magnetic field topology [3].

The influence of the magnetic field on the performance and plasma characteristics of HT with a conventional design has been studied and reported in the literature [4-8]. Notice that a modified external magnetic circuit can also be used to steer the thrust vector direction [9]-[10]. Hoffer *et al.* have studied the influence of the magnetic field topology on the performance of the NASA-173-v2 5 kW-class HT. The generic magnetic circuit has been modified with two trim coils to obtain an additional control of the magnetic field topography. The use of a trim coil places behind the anode permits to increase the magnetic field gradient inside the thruster channel. When the external trim coil is energized, the magnetic field topology in the plume downstream the thruster channel changes; especially the inclination of the lines modifies the magnetic lens [4], [5]. Nevertheless, in all cases, the change of one parameter of the magnetic topology induces a change in another characteristic of the initial magnetic field. In other words, the standard design of a magnetic circuit does not allow to solely vary one degree of freedom without affecting the others.

This paper presents a new and versatile magnetic structure that has been mounted in a thruster prototype based on the PPS®1350 architecture. The prototype is named PPS-Flex, as it appears to be extremely flexible in terms of magnetic field configurations. In Section II, we present the specifications and the design of the new magnetic circuit. Section III illustrates several magnetic topologies that can be realized using this new magnetic circuit. We briefly explain the experimental test-bench and illustrate the magnetic field measurements in Section IV. Results of the first test campaign of the PPS-Flex for different magnetic configurations are described in Section V. Conclusions are drawn in Section VI and a roadmap for future works is given.

II. Description of the magnetic circuit

In order to study the impact of the magnetic field on a HT operation, precise specification about magnetic circuit has been defined. First of all, the PPS-Flex magnetic circuit must be compatible with the one of the PPS®1350 thruster [11]. Since many years a large amount of data has been collected about the PPS®1350 Hall thruster, it is of great interest to be able to generate the PPS®1350 magnetic configuration with the new circuit. The PPS®1350 normal topology is therefore the reference topology for this study. The reference magnetic field profile along the channel axis (radial component B_r) is given in Fig. 1a. Second, the proposed magnetic structure must permit to set several magnetic field degrees of freedom simultaneously in an independent manner. Note that this feature makes the PPS-Flex unique. The magnetic degrees of freedom are:

- The axial magnetic field gradient inside and outside the channel,

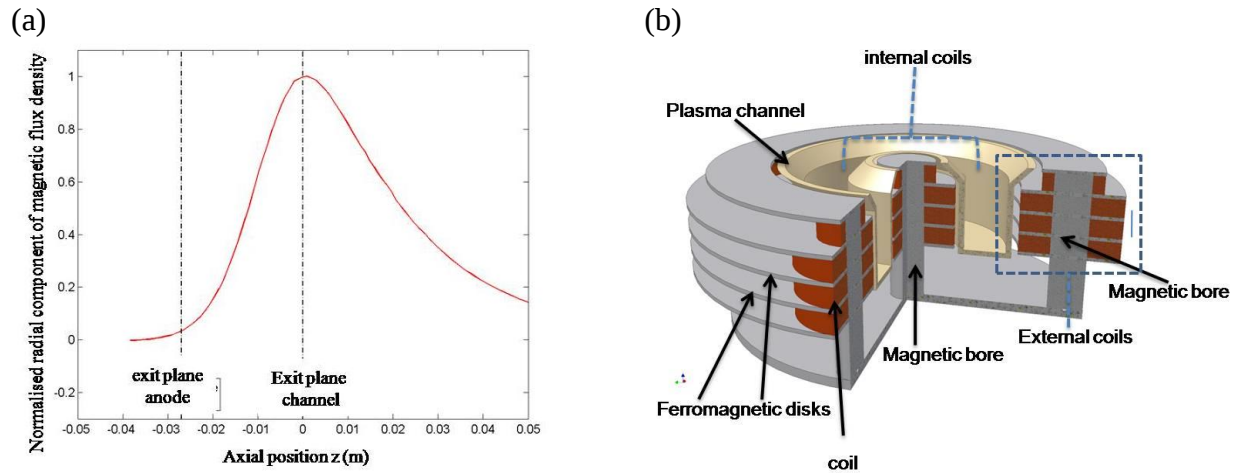


Figure 1: (a) Reference profile of the radial magnetic field strength; (b) Conceptual arrangement of the PPS-Flex thruster with the specific magnetic circuit and the channel.

- The strength of the field (to a small extend with this first version),
- The axial position of the maximum of magnetic field strength,
- The width of the profile,
- The curvature of the lines.

In addition, the possibility to create a zero-magnetic field region near the anode must be taken into account. Finally, in terms of design, the magnetic circuit must be concentric and compatible with the geometry of the channel of PPS®1350 thruster.

The PPS-FLEX magnetic circuit is sketched in Fig. 1b. Because many degrees of freedom are expected, the usual magnetic circuit design, which includes one central coil and four external coils supplied with the same current, is not sufficient. Notice that even if two different power supply units are used, it only permits to change the inclination of the magnetic lens. To drastically increase the range of possible magnetic field configurations, one solution consists in increasing the number of independent coils and separating them with ferromagnetic parts which drive the magnetic flux. Based on the knowledge of some authors in the field of magnetic actuators with slotted armature, the designed magnetic circuit links elementary parts composed of a coil wrapped around a ferromagnetic bore and inserted in two ferromagnetic disks as shown in Fig.1b.

Each element is dedicated to one specific function. The coil generates the magnetic field. The magnetic bore concentrates the magnetic field and the ferromagnetic disks conduct the flux lines to obtain the desired shape of the magnetic field inside and outside the channel. Compared to the conventional PPS®1350 thruster the channel and magnetic circuit have been lengthened. An external conic part has been added, as can be seen in Fig. 1b. The coils and the ferromagnetic parts that make this additional section are necessary to control the axial magnetic field gradient outside the channel. In order to protect those coils from the thermal heat flux and the ion bombardment, the additional section is shielded with a ceramic piece. The conic shape results from an optimization process: the added ceramic does not interact with the main plasma generated outside the cylindrical channel. We must underline that the additional parts can be removed in such a way the PPS-Flex channel becomes similar to the one of the PPS®1350, however, at the expense of magnetic flexibility.

The magnetic circuit is divided into four stages, as shown in Fig. 1b. Four external coils located around the outer wall of the channel and one internal coil wrapped around the central core constitute one stage. Each stage is supplied with the same current. The stage number results from a trade-off between performances and overall dimensions. Each stage provides new degrees of freedom for the generated magnetic field topology. When the stage number increases, the possibilities to vary the magnetic field map increase as well. The magnetic field generated by each coil is active along its axis. Consequently, all coils must be placed along the thruster channel. Increasing the number of

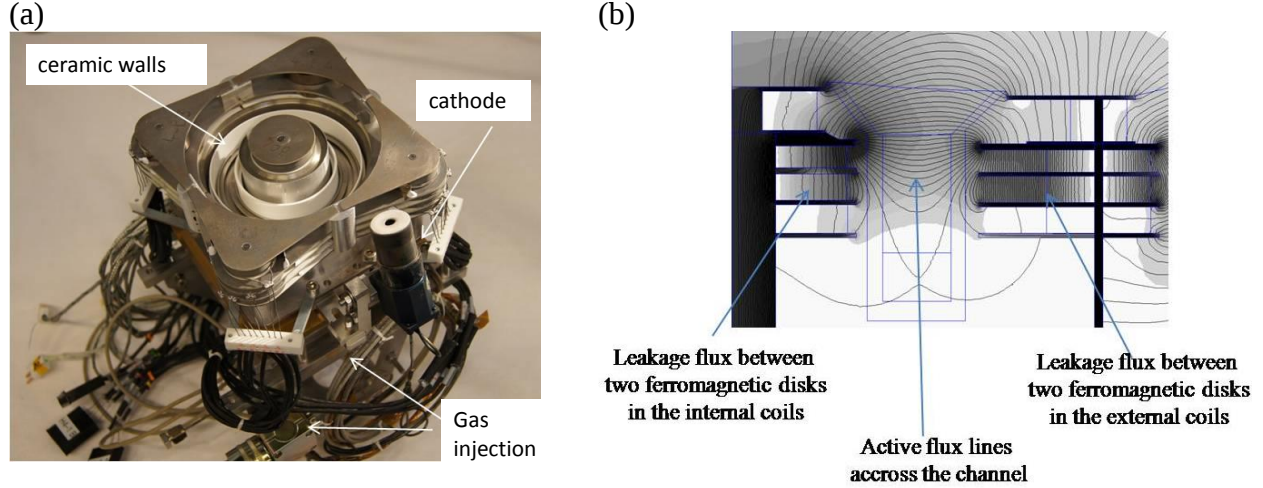


Figure 2: (a) Picture of the PPS-Flex prototype without front ceramic rings; (b) Example of a magnetic field map produced with PPS-Flex (solid blue lines correspond to the ceramic channel).

coils by keeping constant the length of the channel implies a decrease of the thickness of the coils and a decrease of the gap between the dividing ferromagnetic disks, as shown in Fig. 1b. If the length decreases, the magnetic lines of flux can be short circuited between two dividing disk and do not penetrate into the channel. The number of coils must thereby be limited.

In order to find the lowest number of coils, an optimization process based on a parametric study using a finite element magnetic software [12] with a numerical software (MATLAB®) has been carried out. The constraints for this process were the length of the channel and the magnetic specifications. The optimization procedure finally indicates 3 coils along the active PPS®1350-like channel and one more coil in the additional conic section [13].

To obtain homogeneity in the azimuthal direction, the perfect solution consists in designing an axisymmetric magnetic circuit with external coils wrapped around the plasma channel. This arrangement is not satisfying on thermal and experimental points of view. On the one hand, the coil wrapped around the ceramic channel forms a thermal barrier for the energy flux produced by the plasma. On the other hand, this coil configuration does not make easy the experimental characterization of the discharge with wall probes and laser spectroscopy techniques [8]. As a consequence, the magnetic circuit design is made of external coil distributed in a symmetric way along the external circumference of the channel, as illustrated in Fig.1b. The choice for the materials is detailed in Ref. [14].

The total number of coils for the PPS-Flex is in fact 22. The magnetic assembly includes the 20 coils previously described and shown in Fig. 1b. In addition, 2 complementary coils are located behind the back wall of the channels. They allow to better control the zero-field region near the anode and the internal gradients. That means the total number of degree of freedom is 10: 4 internal coils, 4 external coil assemblies (the four coils per stage are connected in series) and the two back coils. This feature makes this thruster unique. Note that the PPS-Flex operation requires to independently controlling 10 power supplies only for the B-field generation.

A photograph of the PPS-Flex prototype is shown in Fig. 2a without the front ceramic elements. Figure 2b is an example of the magnetic field lines with a convex magnetic lens as for the normal PPS®1350 configuration.

III. Magnetic flexibility

We illustrate in this section the capability of the magnetic circuit to generate various magnetic field topologies. The profile in red in the following figures corresponds to the reference radial magnetic field profile, that means for the normal conditions of the PPS®1350.

Figure 3a shows the change in the gradient of the magnetic field along the x direction when the maximum of magnetic field is located in the exit plane. Figure 3b also demonstrates it is possible to control independently the gradient inside and outside the channel without modifying the magnitude and position of the magnetic field. Varying the DC current flowing in coils allows changing significantly the magnetic field gradient. The rate of change reaches 25% upstream and 38% downstream of the plasma channel exit plane, respectively.

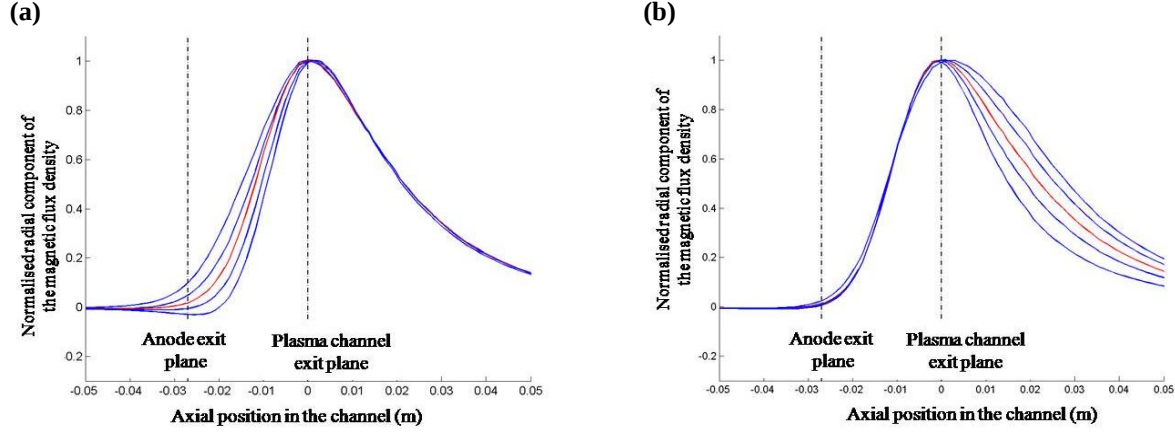


Figure 3: Control of the gradient of the magnetic field radial component (a) upstream of the exit plane, and (b) downstream of the exit plane.

Figure 4a illustrates the change in the magnetic field strength for different coil currents. The PPS-Flex permits to vary the maximum value of the magnetic field by $\pm 30\%$ without affecting the other characteristics. Moreover, figure 4b shows the possibility to change the position of the maximum of the magnetic field along the thruster channel centerline.

By modifying the axial magnetic field strength close to the channel exhaust, we are able to change the inclination of the magnetic field lines, see Fig. 5. With the PPS-Flex this angle can be adjusted from -6° to $+12^\circ$.

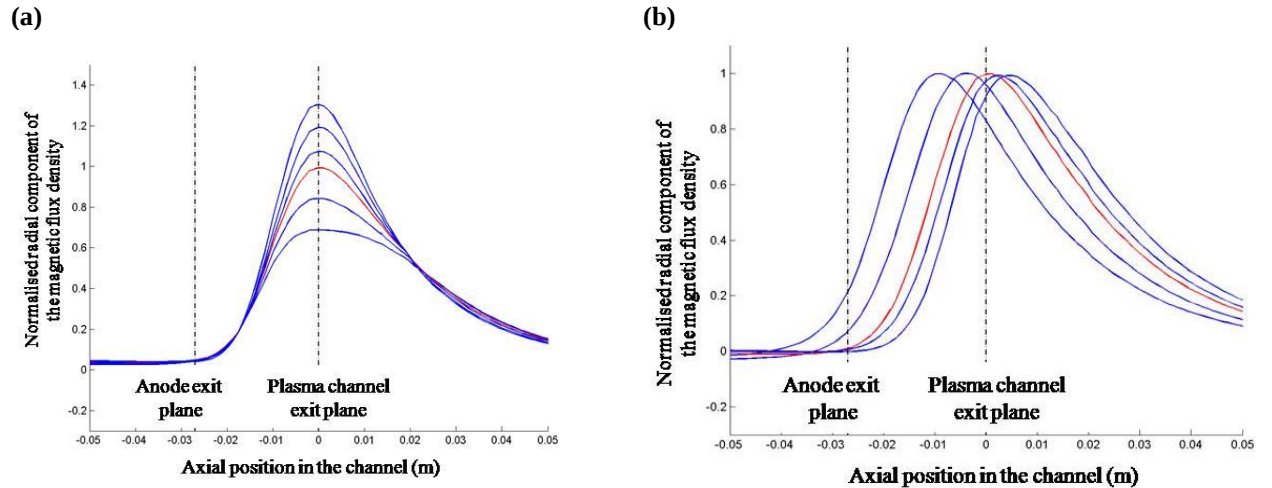


Figure 4: (a) Control of the maximum magnetic field strength; (b) Control of the position of the maximum of the magnetic field intensity.

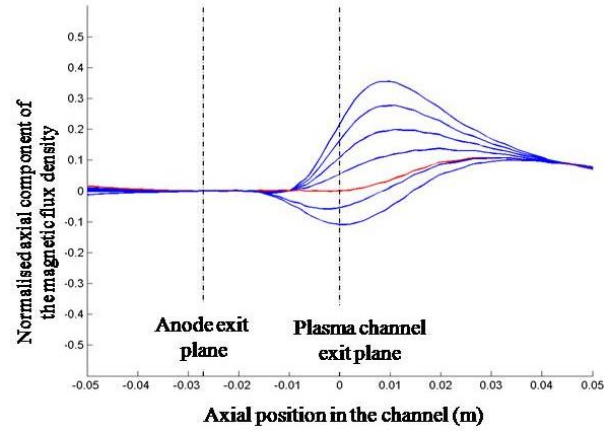


Figure 5: Control of the distribution of the axial magnetic field component.

Many studies show that a vanishing magnetic field at the anode tends to improve HT performances [4], [6]. This zero magnetic field region can be obtained in conventional HTs by a supplementary coil positioned behind the anode, but the change rate is very limited and it does not permit to quantify the average impact on the plasma. The degrees of freedom available with the PPS-Flex permit to create and move a zero magnetic field zone. This specific zone can be shifted in the three direction and located anywhere near the anode plane as illustrated in Fig. 6. Note that to generate and control a zero B-field region, one needs to power the 2 back coils as well.

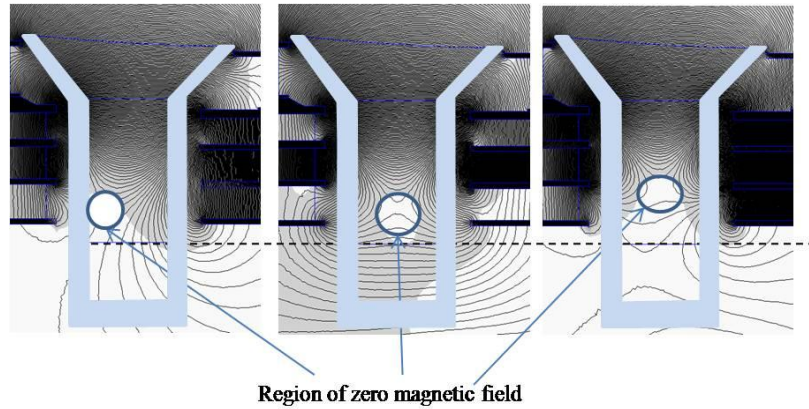


Figure 6: Magnetic topology with a zero-magnetic field region.

IV. Magnetic characterization

The experimental validation has consisted in verifying that the PPS-Flex is able to generate all magnetic maps given in the specifications. A dedicated test-bench has been developed. A picture of the bench is displayed in Fig. 7. It includes a Gaussmeter with a 3-axis probe and a remote controlled (x, y, z) translation stage. The displacement unit permits to place the PPS-Flex at any specified radial and angular position in a reference cylindrical frame. Besides, the magnetic probe can be moved in the direction of the thruster axis and it can cover the entire length of the plasma channel. The power supply of the PPS-Flex is made of 8 computer controlled regulated DC power supplies. Two other hand operated power supplies are employed for the back coils. Home-made software is used to control the 8 power supplies and the motorized stages. Acquired data allows to construct 2D magnetic maps and to compute field lines and vector.

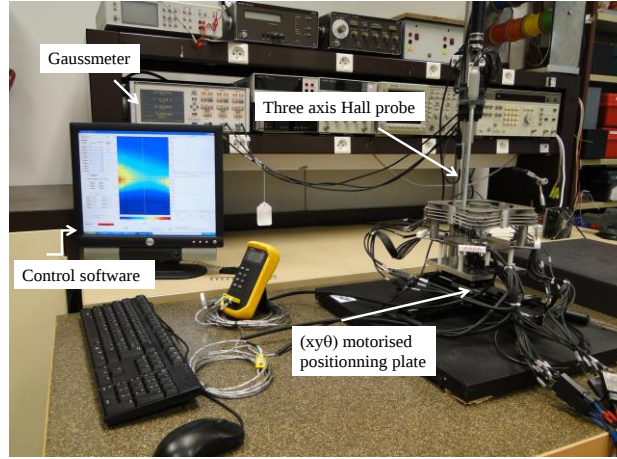


Figure 7: Picture of the test bench developed to measure the magnetic field topology.

We illustrate the measurements of the magnetic field topology in the case where the magnetic field gradient inside the HT channel is changed. Figure 8a shows contour-plots of the magnetic field strength for two conditions. On the left hand side, the currents in the coils have been adjusted in order to reduce the gradient, while, on the right hand side, the adjustment of the coil currents permits to increase the gradient. Figure 8b shows the distribution of the radial magnetic field along the channel centerline for the same two conditions. The reference profile that corresponds to the PPS®1350 normal conditions is plotted in blue. Notice the slight decrease of the maximum of the magnetic field when the gradient is reduced.

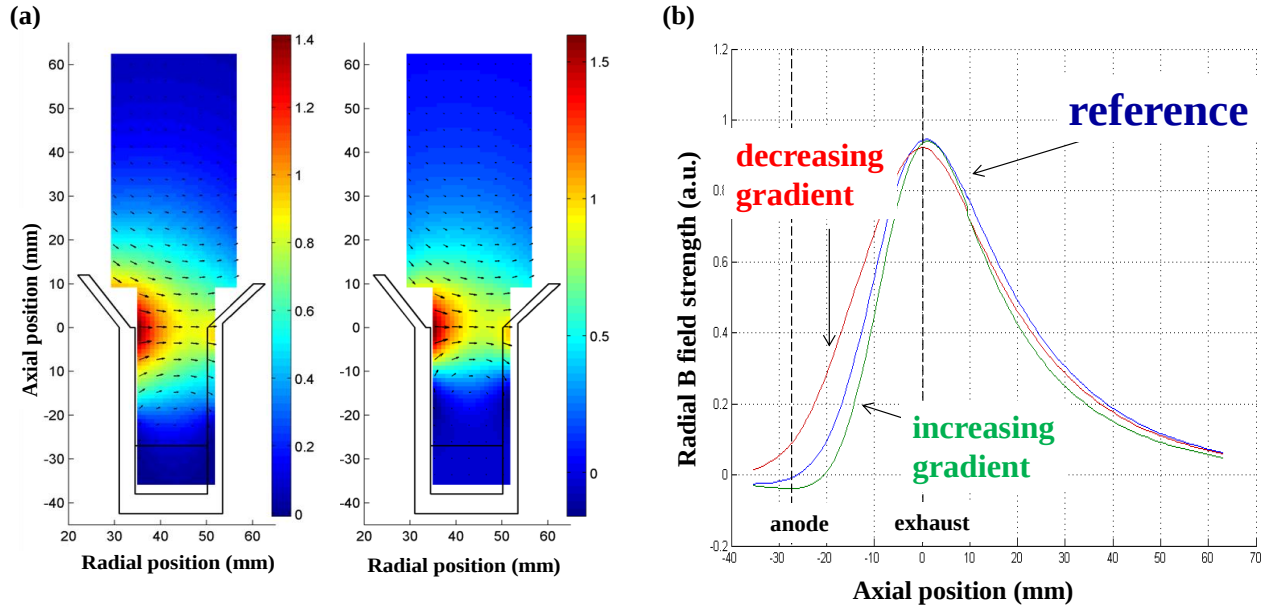


Figure 8: (a) Contour plot of the magnetic field measured for two conditions; (b) Corresponding experimental on-axis distribution of the radial magnetic field in the channel. Magnitudes are given in arbitrary units.

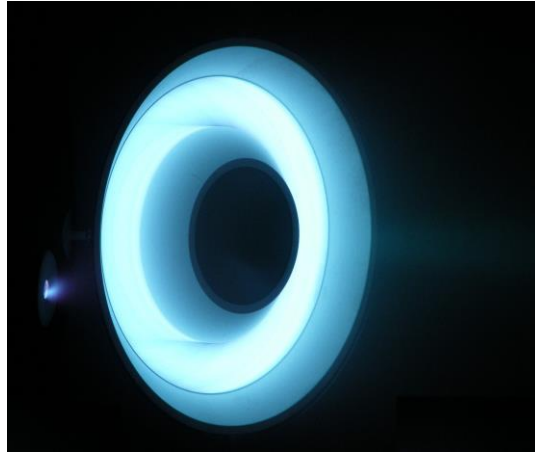


Figure 9: Photograph of the PPS-Flex thruster in operation with xenon as propellant gas.

V. Results of the first test campaign

The PPS-Flex thruster has been fired with xenon as propellant gas in summer 2012 in one of the Snecma vacuum chamber at Vernon in France. The thruster was equipped with BN-SiO₂ walls (channel and conic section). A cold hollow cathode was used as a beam neutralizer. The thruster was operated at a fixed discharge current value of 4.28 A. The discharge voltage was varied between 200 V and 350 V. The input power never exceeded 1500 W to limit the thermal load. The thruster was mounted onto a calibrated thrust balance. A rotating arm equipped with 15 Faraday probe was used to measure the ion current density profile in the plume far-field. The total ion current was computed assuming a cylindrical symmetry of the beam. The divergence half-angle from the thruster centerline θ corresponds here to the half-angle over which the ion current density represents 90 % of the total ion current. A photograph of the PPS-Flex in operation is shown in Fig. 9. The conic part of the channel is clearly seen.

The main objective of this first campaign was twofold, namely: To verify the operation of the thruster for various power levels and to test the flexibility of the system, that means its capability of generating different magnetic field configurations. In total, 13 magnetic topologies have been produced. They included:

- the PPS1350-ML thruster B-field,
- the SPT100 thruster B-field,
- topologies with a steep gradient inside the channel,
- position of the highest intensity,
- topologies with various lens inclination,
- topologies with a zero B-field region.

The 22 coils have been used during the study together with 10 power units. The 13 magnetic configurations are summarized in Table 1. The latter also gives the identification number for the remainder of the paper.

Table 1: Tested PPS-Flex magnetic field configurations

PPS-Flex magnetic configurations			
Number	Investigated parameter	Number	Investigated parameter
1	PPS@1350 (reference)	5	Position along x
2	SPT100	6-10	Lens
3, 4	Gradient inside the channel	11-13	Zero B-field region

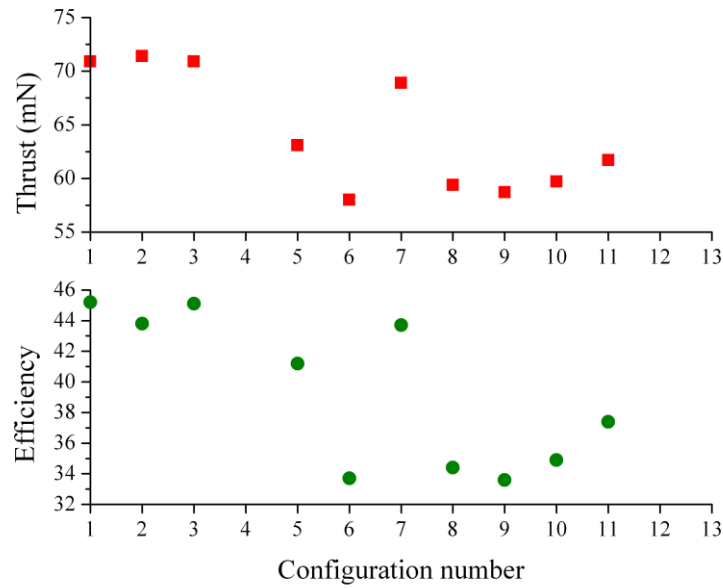


Figure 10: Thrust and total efficiency of the PPS-Flex thruster at 250 V applied voltage (1070 W).

The measured thrust level is given in Fig. 10 for the 13 magnetic configurations previously described. Figure 10 also displays the total efficiency η , which accounts for the cathode gas flow rate. Measurements have been carried out for a discharge voltage of 250 V. The power furnished to the discharge is 1070 W. Configurations 4, 12 and 13 were not stable for this set of operating conditions. Current oscillations were large and the discharge switched-off after a short time span. The highest thrust level and the largest efficiency are reached for the first 3 configurations, which can be considered as standard. The magnetic configuration labeled 7, which exhibits an important lens inclination, gives relatively good performances. However, due to the large inclination angle, the ceramic erosion is significant and the lifetime is certainly limited.

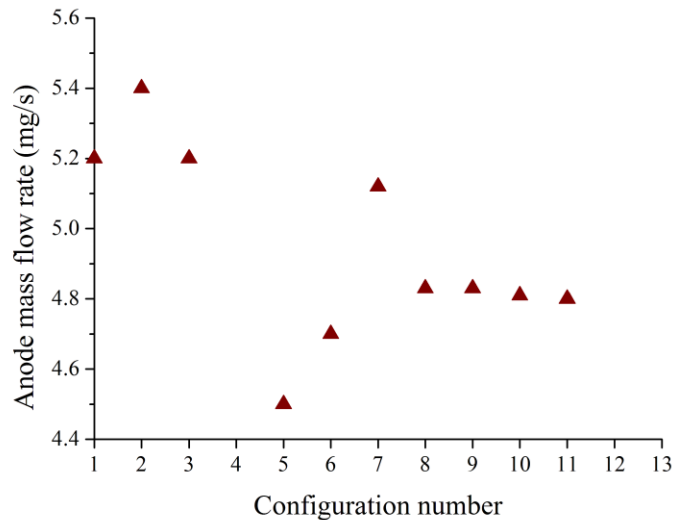


Figure 11: Xenon anode mass flow rate of the PPS-Flex thruster at 250 V applied voltage (4.28 A).

Table 2: Performance data of the PPS-Flex at 250 V.

Experimental data; $U_d = 250$ V						
Number	Parameter	T (mN)	η_i	η	Isp (s)	α (°)
1	PPS®1350	70.9	0.72	0.45	1446	36.7
2	SPT100	71.4	0.71	0.44	1379	35.5
3	Gradient inside	70.9	0.74	0.45	1367	35.6
4	Gradient inside	-	-	-	-	-
5	Position x	63.1	-	0.41	1410	-
6	Lens	58	0.57	0.34	1258	40.5
7	Lens	68.9	0.73	0.44	1371	38.6
8	Lens	59.4	0.59	0.34	1254	39
9	Lens	58.7	0.61	0.33	1237	40.7
10	Lens	59.7	0.58	0.35	1267	40.1
11	Zero B-field	61.7	0.65	0.37	1310	39.8
12	Zero B-field	-	-	-	-	-
13	Zero B-field	-	-	-	-	-

The reference configuration labeled 1 in fact gives values (current, thrust, specific impulse, efficiency...) very close to the ones obtained with the PPS®1350 Hall thruster whatever the discharge voltage. First, it indicates the PPS-Flex magnetic circuit can accurately reproduce the normal PPS®1350 magnetic field map. Second, it shows the weak effect of the additional conic section on the discharge and plume properties. Note that the PPS®1350 magnetic configuration (1) produces performances above the SPT100 configuration (2) as it is in reality.

Figure 11 shows the anode mass flow rate in xenon Φ_a necessary to maintain the discharge current at 4.28 A for the 13 magnetic configuration of the PPS-Flex. In that case the mass flow rate gives information about the ionization efficiency. Φ_a is relatively high for the PPS1350 B-field map, however, it is below the value measured with the SPT100 map. The lowest xenon flow rate is obtained when moving the peak of the B-field axial profile (5). Yet the efficiency is very low with this configuration.

The set of experimental data is summarized in Tab. 2 for a discharge voltage of 250 V. The specific impulse Isp is computed from the thrust level. The quantity η_i is the ionization efficiency and α is the beam divergence half-angle. The largest Isp is reached with the PPS1350 configuration, which also gives a low beam divergence. The propellant utilization is improved when the gradient inside the cavity is steeper.

VI. Conclusion and prospects

The magnetic field topology in a Hall thruster has been derived from the past experience of former Soviet Union scientists. The current magnetic field topology has been defined to warrant a high performance level when thrusters operate around the normal condition. However, the flexibility of the magnetic architecture does not permit to explore a large range of magnetic field configurations (magnitude, position, gradients, width, and so on) that could enable to improve the performances, the overall operation envelope as well as the lifetime.

A flexible magnetic field circuit has recently been designed and built. The circuit is composed of a central magnetic part and an external magnetic part wrapped around the channel. Each part is made with four stages, each of them including one inner coil and 4 outer coils distributed around the channel. Each stage is separated by thin ferromagnetic elements which permit to guide the magnetic flux lines in the desired location. The circuit has been tested in air and characterized using a motorized test bench able to measure the complete 3D magnetic map. Characterization and computer simulations reveal the magnetic circuit offers the possibility to separately control:

- The magnitude,
- The gradient inside and outside the channel,
- The axial position of the maximum,
- The width of the profile,
- The curvature of the lines,
- The existence of a region with zero B-field close to the anode.

A first test campaign was performed in summer 2012 in one of the Snecma vacuum chamber at Vernon in France. The PPS-Flex thruster has been fired with xenon for 13 different magnetic field topologies for an applied voltage ranging from 200 V up to 350 V. Measurements clearly demonstrated the capability and the versatility of the thruster in terms of magnetic configurations.

A second test campaign will occur in the very near future. The objective is now to explore a vast set of magnetic topologies by pushing the PPS-Flex up to its limit. In addition to thrust and ion current density measurements, we plan to acquire the discharge current time-series and to measure the ion velocity.

Acknowledgments

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