

A new flexible magnetic circuit for a Hall effect thruster

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Abstract: This paper deals with a new magnetic circuit dedicated to Hall effect Thruster. Compared with conventional magnetic circuit used in Hall effect Thruster, the aim of this new magnetic circuit is to control many characteristics on the magnetic topology generated in the plasma channel. From a reference magnetic topology generated in a plasma channel given in specifications, the magnetic circuit must be able to vary the magnetic field maximal value in the plasma channel, the gradient of the magnetic field at the exit plane of the plasma channel and many other characteristics. This paper presents first the specifications of the magnetic circuit. The second part details the design of the magnetic circuit taking into account the environmental conditions operation in spatial experiment test bench. Finally, the last part illustrates several magnetic topologies feasible by this new magnetic circuit.

I. Introduction

Hall effect thrusters (HETs) are plasma thrusters used on board telecommunication satellites for propulsion tasks mainly for geostationary station keeping. Contrary to ion engines, no accelerating grids are used in a HET. The electric field penetrates inside the plasma by reducing the electron conductivity with the help of a transverse magnetic field. A cylindrical geometry is used to permit an electron drift without closure in the $\mathbf{E} \times \mathbf{B}$ direction. The channel where the discharge is ignited is constituted with ceramic walls to isolate the plasma region from the magnetic circuit. The anode, located at the base of the channel, serves also as a gas distributor. The cathode, located outside the channel, provides primary electrons used to initiate the discharge.

The magnetic structure of a conventional HET is constituted of a magnetic circuit with two poles pieces, cores and two magnetic screens, one internal coil and four external coils. Along the channel centerline, the axial magnetic field gradient is positive inside the thruster channel and negative outside. The maximum of magnetic field $B_{\max}$ is located in the exit plane. The magnetic field lines has a concave shape. The influence of the magnetic field on the thruster performance and plasma characteristics has been studied and reported in the literature [1] [2][3] [4] [5]. As an example, the use of trim coils permits to increase the magnetic field gradient inside the thruster channel [1]. However, the use of a rear trim coil also affects the magnitude of maximum magnetic field in the exit plane. The generic magnetic circuit does not permit to independently study magnetic configurations where the magnetic field gradient is changed without modifying the maximum of magnetic field and vice-versa.

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II. A parametric Hall-effect thruster : Principle and architecture

A. Specifications

In order to study the impact of the magnetic field in Hall thruster a precise specification about magnetic circuit has been defined. First of all the magnetic circuit must be compatible with the PPS1350ML [5]. Since many years many data have been collected from this Hall thruster and it would be interesting to compare and to use those values with another plasma source able to generate similar magnetic configuration. Consequently the required specifications are listed below :

- The conventional and reference curve of the axial profile of the radial magnetic field component must be superposed to the curve illustrated in Figure 1

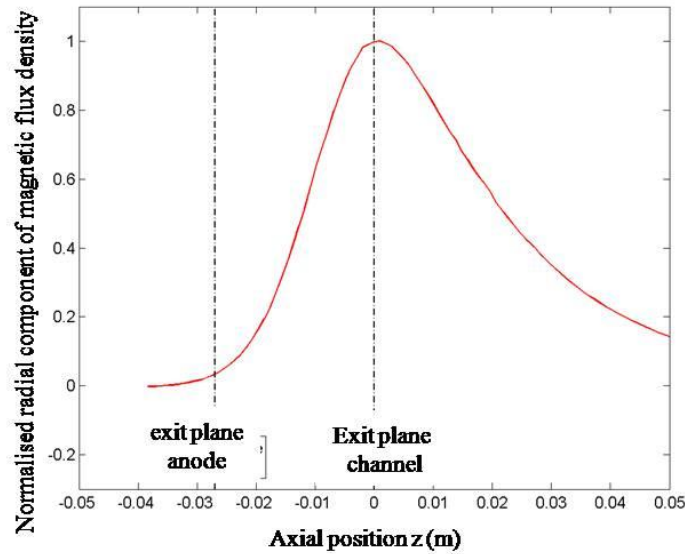


Figure 1. Reference curve of normalised radial component of magnetic flux density

- The axial magnetic field gradient must be controlled so that a positive value inside the channel and a negative value outside the channel can be applied.
- The magnitude of the maximal radial component of the magnetic field in the center of the channel must be controlled
- The location of the magnetic field maximal value outside the channel must be controlled. It must be possible to translate this value along the axial axis
- The magnetic field lens must be controlled
- A zone with zero magnetic field must be available if necessary
- The magnetic field magnitude in the anode plane must be controlled.
- The magnetic circuit is concentric and designed around the channel of PPS1350

B. Design of a the parametric magnetic circuit

In a magnetic point of view, those specifications require a magnetic circuit with many degrees of freedom. The usual magnetic circuits which include one central coil and four external coils supplied by the same current is not sufficient even if two stream coils can be used to extend the potential modifications of the magnetic configuration. To increase the range of magnetic field change, one solution consists in increasing the number of independent coils and separating them by ferromagnetic parts which permits to well canalize the curl of the magnetic flux. Exploiting the knowledge in magnetic actuators with slotted armature, the designed magnetic circuit links elementary part constituted by a coil wound around a ferromagnetic bore and inserted in two ferromagnetic disks as shown in Figure 2.

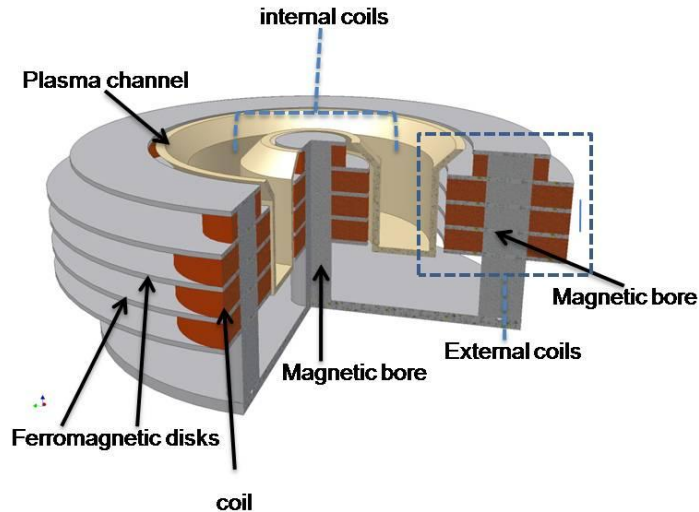


Figure 2. Principle of the parametric magnetic circuit (PPS-FLEX) and its plasma channel

Each part 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 the magnetic field in the channel. Compared to the conventional PPS1350 the designed channel and magnetic circuit have been extended. An external conic part has been added, as we see in Figure 2. The coils and the ferromagnetic parts that constitute this additional part are necessary to well control the axial magnetic field gradient. In order to protect those coils from the thermal flux radiated by the plasma, the external part is also covered with a ceramic. This shape results from a optimization process so that the added ceramic does not impact the plasma generated outside the cylindrical channel. Let us underline that those added parts can be dismantled and the PPS-FLEX recovers the same channel and the same bulk as the PPS1350.

The magnetic circuit is divided into four stages. Each stage, constituted by four external coils located around the outer periphery of the channel and one internal coil wound around the central bore, are supplied by the same current. The stage number results from a compromise between performances and overall dimensions. Each added stage provides a new degree of freedom for the generated magnetic field topology. If the stage number increases, the possibilities to vary the magnetic field map increase. The magnetic field generated by each coil is active face to the coil. Consequently all the coils must be located along the thruster channel. Increasing the number of coils by keeping constant the length of the channel implies to decrease the thickness of the coil and to reduce the axial length between the dividing ferromagnetic disks as show in Figure 3. If this axial length decreases, the flux lines can be short circuited between two dividing disk and do not go across the channel. The number of coils must be limited.

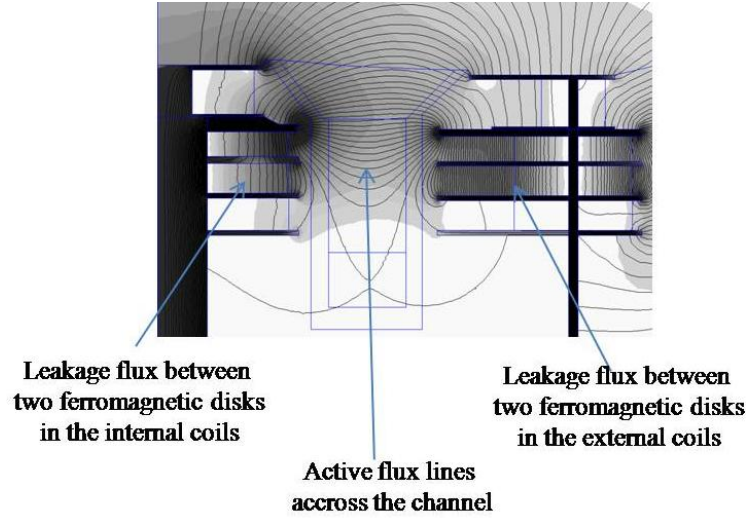


Figure 3. Curl of the flux line with leakage flux

In order to find the minimal number of coils, an optimization process based on a parametric study using finite element magnetic software (FEMM) [10] and numerical software (Matlab) has been carried out [8]. The constraints of this process were the length of the channel and the magnetic specifications and finally the results give 3 coils along the active channel and one added coil in the extended channel [8].

To obtain an azimuthal homogeneity, the perfect solution consists in designing an axi-symetrical magnetic circuit with external coils wound around the plasma channel. This arrangement is not satisfying if looking at the thermal and experimental points of view. The coil wound round the plasma channel constitutes in one hand a thermal barrier for the thermal flux radiated by the plasma. In other hand this coil configuration does not make easy the characterization of the plasma in particular if the LIF measure is required [6]. Consequently, the magnetic circuit designed is made up of external coil distributed along the external diameter of the plasma channel as illustrated in Figure 2.

III. Design of the PPS-FLEX

A. Material choices

Magnetic, mechanical and thermal characteristics of the material must be taken into account to optimize the design of the magnetic circuit. Considering the ferromagnetic parts, the “Armco iron” has been chosen. Iron steel is not necessary because the coils are supplied by DC current (no iron losses by eddy currents) and the cross section is very thin. A specific conducting cable has been used for the coils. This cable named “cerafil” is made by a cooper section surrounded of a thin ceramic sheath. This cable has the same conductivity than the cooper but its maximal temperature which can reach 600°C in continuous operating cycle is compatible with environmental conditions of operation. The cerafil is very brittle and a electrical insulation is necessary to prevent any short circuit between turns and between turn and ferromagnetic parts. The insulating process has been made with a thin layer of alumine. The PPS-FLEX has been designed and optimized from the methodology explained in paragraph B. The final sizes are summarized in the table 1.

Lenght whithout the last stage	78mm
Final lenght	90mm
External diameter	240mm
Number of stage	3 + 1 dismountable
External coils number	4
Internal coils number	4
External coil number	16
rear optional coils	2

Table 1 Sizes and main characteristics of the PPS-FLEX

B. Final design and prototype

The prototyping has required several experimentations on elementary parts in order to validate the material choices. Thermal response and insulation resistance testing have been carried out on simple wound ferromagnetic pieces before to build the final magnetic circuit illustrated in Figure 4.

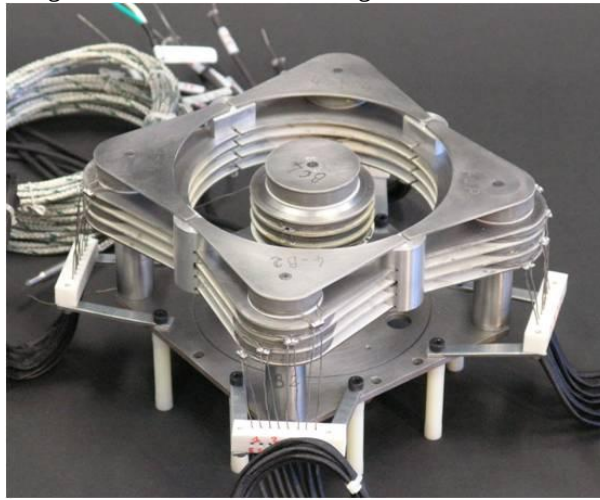


Figure 4. Magnetic circuit of the PPS-FLEX

IV. Magnetic characterization of the PPS-FLEX

The experiment validation has consisted in verifying that the PPS-FLEX is able to generate in the plasma channel all magnetic cartographies given in the specifications. A specific test bench has been developed. It includes a gaussmeter with a tree axes probe and a motorized plate which permits to locate the PPS-FLEX at any specified radial and angular position in a referenced cylindrical frame. The probe is driven along the axial axes to cover the length of the plasma channel. The power supply of the PPS-FLEX is made of 8 regulated DC power supply and specific software is implemented to control the power supply and the motorized plate in order to draw required curves and magnetic maps in 2D planes.

A. Gradient modification

We illustrate in Figure 5 the modification of the gradient of the magnetic field when the maximum of magnetic field is located in the exit plane. The curves show that it is possible to control independently the gradient under and over the exit plane without to affect the global characteristics of the magnetic flux density (magnitude and position of the maximal value). Varying the DC supply current from 0 to the rated value allow to significantly change the gradient. The rates of variation reach 25% upstream and 38% downstream to the plasma channel exit plan.

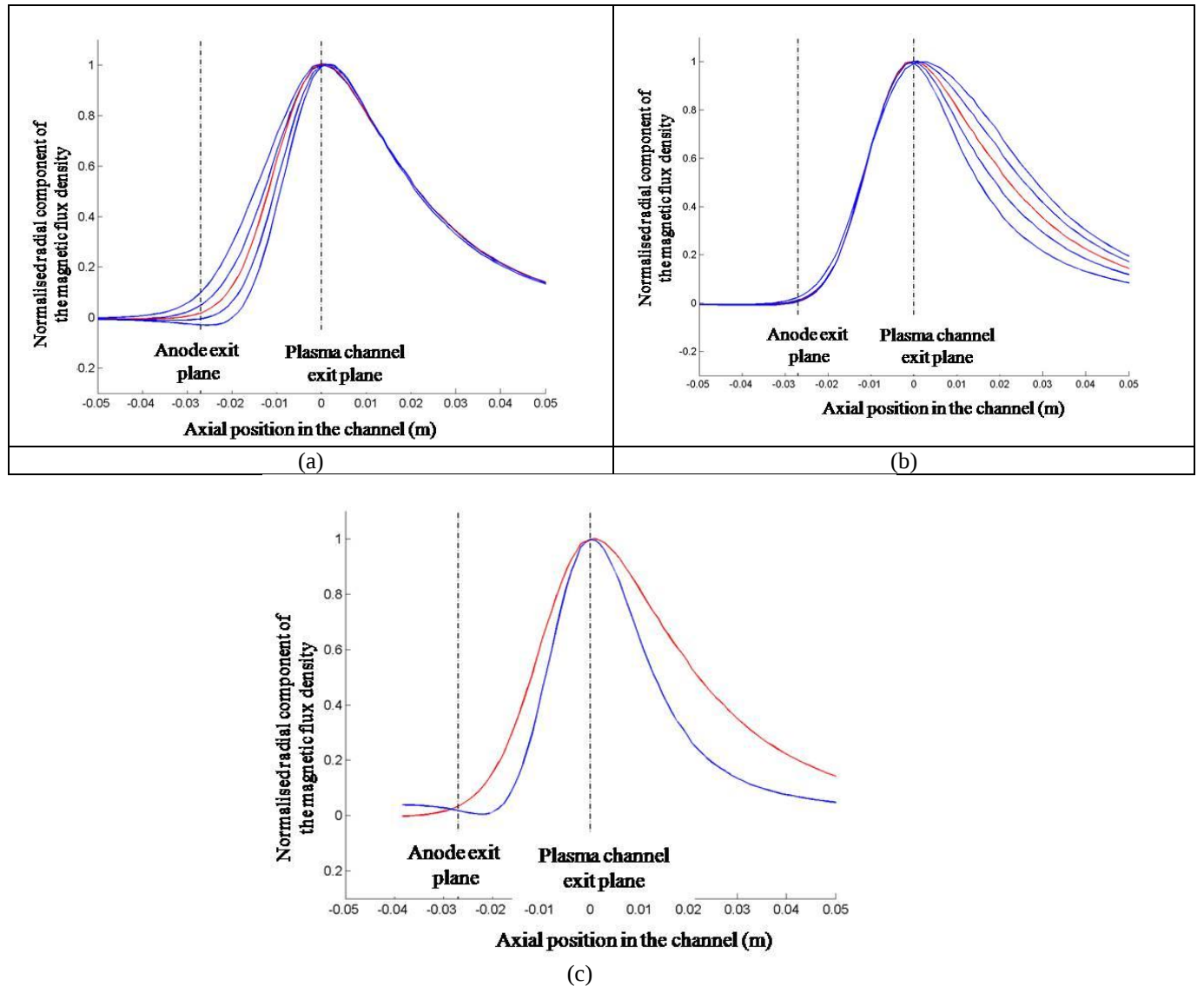


Figure 5. Control of the radial magnetic flux density gradient on the plasma channel (a) upstream to the exit channel plan (b) downstream to the exit channel plan (c) upstream and downstream to the exit channel plan

B. Magnitude and positioning control of the maximal magnetic flux density in the channel

The impact of the maximal magnetic flux density in the channel center should be more studied. But in usual Hall thruster which has no many degrees of freedom for the magnetic field control, the change of the maximal magnetic flux density leads to a significant modification of the magnetic field map in the channel. The PPS-FLEX permits to vary the maximal value of the magnetic flux density without to affect the other characteristics as shown in Figure 6(a). Figure 6.b shows moreover the possibility to change the position of the maximal magnitude along the channel.

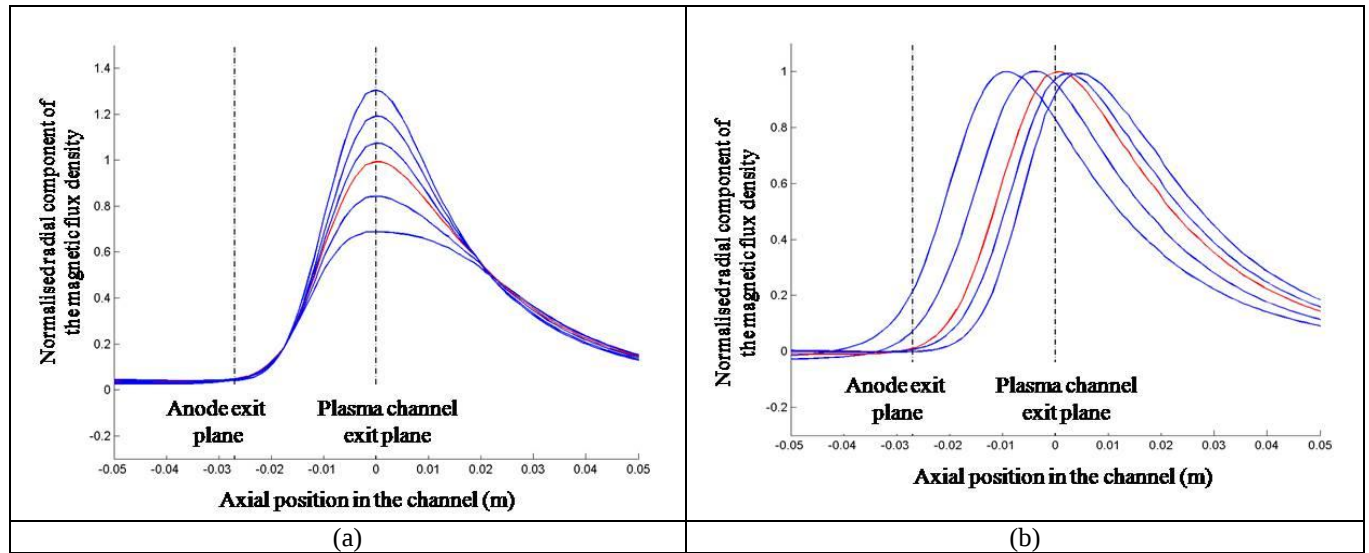


Figure 6. Radial magnetic flux density in the channel (a) maximal magnitude control (b) maximal value positioning control

In the both cases the rate of change is around $\pm 30\%$ from the reference curve given in Figure 1.

C. Magnetic lens control

The angle between the flux line and the exit plan of the plasma channel modifies the divergence and the plasma plume focusing [7]. With the PPS-FLEX this angle is controllable from -6° to 12° as shown in Fig.7.

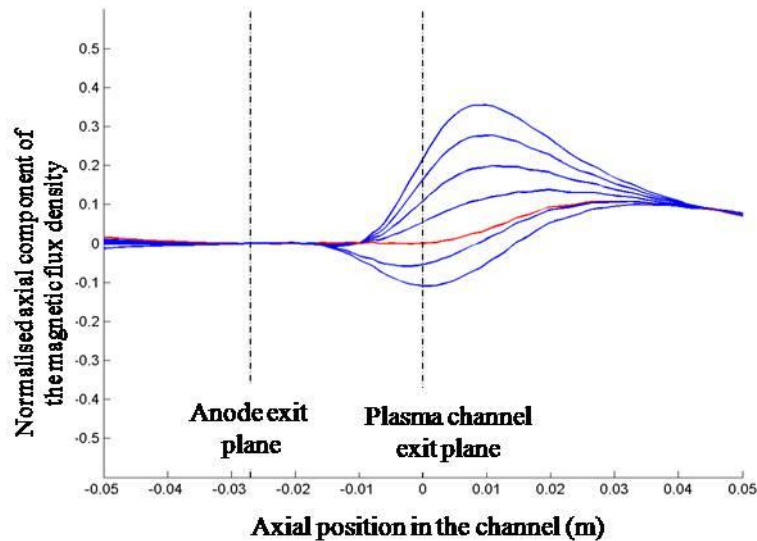


Figure 7. Axial component of magnetic flux density along the channel

D. Zero magnetic field control

Many studies show that a vanishing magnetic field at the anode tends to improve performances of the hall thruster [3][9]. This zero magnetic field region can be obtained in usual hall thruster by a supplementary coil

positioned behind the anode, but the change rate is very limited and doesn't permit to quantify the average impact on the plasma. The degrees of freedom available in the PPS-FLEX permit without any added coil to create and modify this zero magnetic field. But this specific zero zone can be extended in the three axes and located anywhere near the anode plane if two rear coils are used as illustrated in Fig.8.

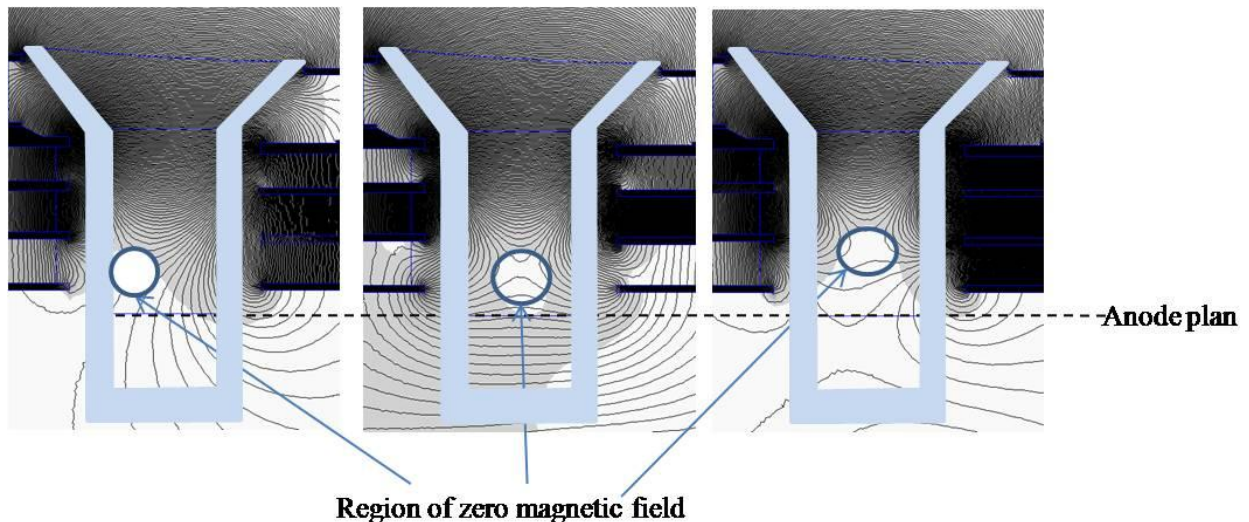


Figure 8. Magnetic field topography in the plasma channel with a zero magnetic field region

V. Conclusion

The design of the magnetic field topology in a Hall effect thruster has began now since more 30 years and the actual magnetic field topology has been defined for thruster operation for nominal conditions. However, the flexibility of the magnetic field structure does not permit to explore a large range of magnetic field modifications (maximum magnitude, position of the maximum, gradient, etc.) that could be useful for future missions.

A flexible magnetic field circuit has been defined and realized. The circuit is constituted by an central magnetic part and a external magnetic part located around the channel plasma. Each part is designed with four stages, each including one internal coil in the inner diameter of the plasma channel and 4 external coils distributed around the outer diameter of the plasma channel. Each coil stage is separated by thin ferromagnetic parts which permit to guide the magnetic flux lines in desired location. The circuit has been built and characterized in a motorized test bench which permit to trace the magnetic field cartographies generated in the plasma channel. We have demonstrated that the magnetic circuit we propose can control separately :

- the magnitude of the magnetic field
- the magnetic field gradient inside and outside the channel
- the axial position of the maximum of magnetic field
- the magnetic field lens
- the zero magnetic field region

The illustrated results showed the possibilities to modify those magnetic characteristic from a well-known reference curve. But one other big advantage of this circuit consists in defining any magnetic field topologies. Consequently it is possible to test new magnetic configurations which are very different from those reached by usual Hall thruster. Consequently the PPLEX should permit :

- to study thoroughly the knowledge of interactions between plasma and magnetic field
- to optimize the magnetic field topology in usual Hall Effect Thruster
- to investigate new Hall Effect Thruster from a specific magnetic field map

We plan now to test the flexible magnetic circuit in the PIVOINE vacuum chamber.

Acknowledgments

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