Chapter 8

Long-Life Technology for Space Flight Hall Thrusters

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Additional information is available at the end of the chapter

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Abstract

The vastly improved durability of spacecrafts, coupled with the simultaneous continuous development of thrusters for high power output, has created a strong demand for Hall thrusters (HT) with long service lives. However, erosion of the discharge channel walls by high-energy ions is the most impactful and visible process that limits the lifetime of the thruster. This process is very sensitive to the operation mode of the thruster and the corresponding power density. We hereby present the results of our investigation on the factors that limit the lifetime of Hall thrusters, and three proven techniques for improving longevity of use including magnetic shielding (MS), wall-less technology, and aft-magnetic fields with large gradient.

Keywords: Hall thruster, long life, magnetic shield, wall-less, aft-magnetic

1. Introduction

The development of space propulsion technology is the cornerstone of development in the aerospace industry. With the rapid development of a wide range of satellite and spacecraft technologies, the demand for space transportation systems is on the rise. Electric propulsion technology is widely used in spacecrafts due to its high specific impulse, compact structure, low propellant consumption, and other advantages. The Hall thruster is currently one of the most widely used electric propulsion technologies at a global level [1].

Hall thrusters (HT), also called stationary plasma thrusters (SPT), were invented in the 1960s, and an early model was first used to transport a Russian satellite (METEOR-18) on December 29, 1971 [2]. The number of SPTs used for scientific and commercial space missions in the United States, Russia, Europe, and Japan is on the rise. The United States involved some of the original work on Hall Thruster in the early and mid-1960s [3–6]. However, interest in that particular accelerator was considerably less than that in ion thrusters. Russia has played a dominant role in the development of SPTs until relatively recently, when the USA, Europe, and Japan began to develop a strong interest in SPTs in the early 1990s. This resurgence of interest has generated a strong recovery in related research and development.

Figure 1 shows a schematic of a common Hall thruster. The basic process of operation begins with the release of electrons from a cathode, which enter a chamber and are subjected to a circumferential Hall drift movement by an orthogonal, axial electric field, and a magnetic field that acts primarily in the radial direction. Neutral atoms that are injected through an anode/gas distributor collide with the electrons in the closed drift and are ionized. Although the magnetic field is strong enough to lock the electrons in a circumferential drift within the discharge channel, its intensity is not sufficiently strong to affect the ions, which are accelerated by the axial electric field. An axial electron flux equal to that of the ion reaches the anode due to the cross-field mobility that often exceeds classical values. The cathode can provide the same electron flux to neutralize the exhausted ions. Therefore, quasi-neutrality is maintained throughout the discharge channel and the plume, and there is consequently no space-charge limitation on the acceleration. Therefore, the thrust density of SPTs is relatively high, compared to that of conventional electrostatic propulsion devices [7].

At present, commercial spacecrafts require thrusters that are capable of trouble-free operation for over 8000 h; however, conventional HTs have a relatively short operational lifetime. Thus, the development of long-life technology for Hall thrusters is significant.

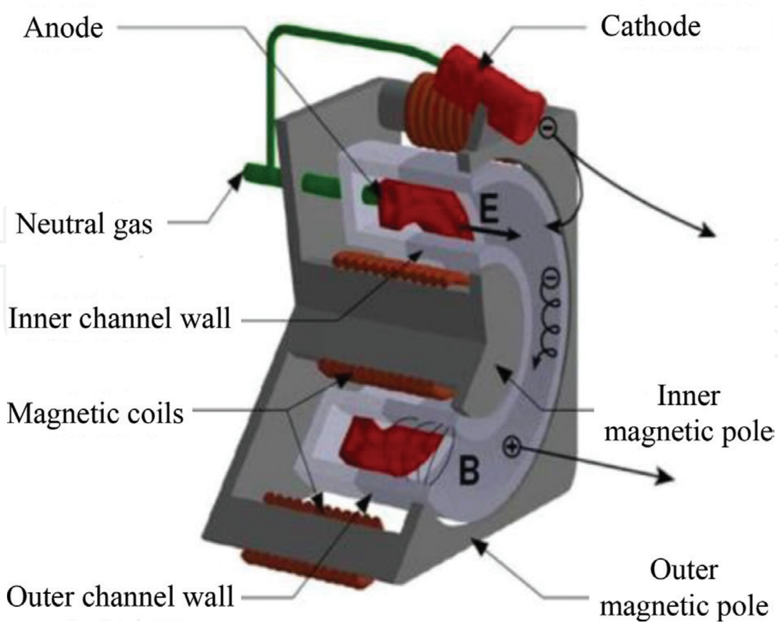

Figure 1. Schematic of a Hall thruster.

2. Long-life limitations of space flight Hall thrusters

Improvements in the operational lifetime of spacecrafts, and the continuous development of high-power thrusters, have resulted in an increasing demand for Hall thrusters with a long service life. There are several physical processes that limit the lifetime and reliability of Hall thrusters. These include [8] erosion of the cathode and magnetic system elements by the accelerated primary and secondary ions and the erosion of cathode's thermoemitter by ions which are accelerated in the near-cathode potential drop in the hollow cathode discharge plasma. Additional processes include oxidization of the getter, contaminated Xe gas flowing through the cathode, evaporation of the thermoemitter and heater materials. Finally, suboptimal temperatures under operation conditions, degradation of insulating and structural element materials, operation in space under increased temperature and radiation factor's impact, mechanical deformation and cracking of the heater, cathode and accelerator materials, due to the thermal shocks which occur when the thruster is started, can all have undesired effects.

The erosion of the discharge channel walls by high-energy ions is the most impactful and notable factor which limits the thruster's lifetime. This process is most sensitive to the thruster's operation mode and the corresponding power density [9, 10]. **Figure 2** shows photographs of the channel geometry of a PPS 1350-GQM thruster after 4200 h of operation. The interaction between the plasma and the wall causes power deposition on the channel wall and other structure components. The magnetic field topology leads directly to the large particle flux

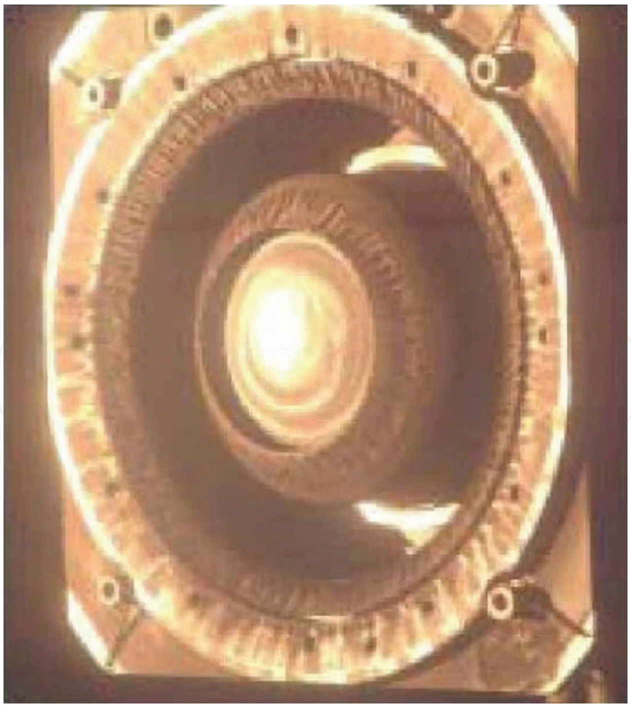

Figure 2. Channel geometry of a PPS 1350-GQM thruster after 4200 h of operation.

with high energy, which is also directed toward the channel walls. In the discharge channel, the atoms undergo diffusion movement before ionization, which results in a radial motion component. The ions that are generated via the ionization process acquire the initial velocity of the atom and a radial velocity component. This results in an acceleration of the ion beam along the radial direction. In addition, the sheath and the presheath structures which are formed by the interaction of the plasma and channel walls also generate a radial electric field, which leads to radial ion divergence. Due to the influence of various physical factors mentioned above, the ion beam will diverge in the channel. In the acceleration zone, a portion of the high-energy ions will not be able to directly exit the channel. Instead, the wall material is sputtered and bombarded. When the bombardment energy is greater than the binding energy of the atoms in the wall, the wall material is sputtered and the geometrical morphology of the channel wall is altered [11, 12].

Long-term ion bombardment of the channel wall causes erosion, and the resulting change in the channel's geometry alters the optimum working condition of the thruster, which results in a decline in performance; more importantly, the breakdown of the channel's ceramic causes the magnetic pole to be exposed to the plasma, which would affect this field. Eventually, the performance of the Hall thruster is significantly affected, resulting in eventual failure. The end of the lifetime of a Hall thruster is generally accepted as the point of time when the channel is completely eroded by ion bombardment, and the magnetic pole is exposed to the plasma.

3. Magnetic shielding technology

During the years 2007 and 2009, Aerojet and Lockheed Martin Space Systems Company demonstrated the extension of the working hours of the qualification model (BPT-4000 4.5 kW HT) over 10,400 h. Most significantly, no measurable erosion of the insulator ring was observed from 5600 h to 10,400 h, which indicated that the thruster had achieved a "zero" erosion configuration [13, 14]. These improvements are the result of the topological structure of the magnetic field near the erosion surface. Jet Propulsion Laboratory (JPL) describes this process as "magnetic shielding (MS)." **Figure 3** shows the design principles involved in a magnetically shielded (MS) configuration, compared to an unshielded (US) configuration. In the US configuration, the magnetic lines near the channel's exit are almost perpendicular to the channel walls; however, the magnetic field lines of the MS configuration extend to the acceleration region deep within the channel and are arranged close to the ceramic walls without intersecting it. This is called the "grazing line," which effectively inhibits cavity wall erosion by high-energy ions.

The electron number density (*ne*) in HTs is so low that collisions between electrons and gases have little influence on the $E \times B$ drift (where E and B denote the electric and magnetic fields, respectively) or Hall drift, and an important current, the Hall current, is produced in a circumferential direction. The electron parameter, $\Omega_e \equiv \omega_{ce}/\upsilon_e \gg 1$, where $\omega_{ce}$is the electron gyro-frequency and υ_e is the total collision frequency. Thus, electron temperature (*Te*) stays nearly constant along the magnetic field lines.

$$\nabla_{//} T_e \approx 0 \tag{1}$$

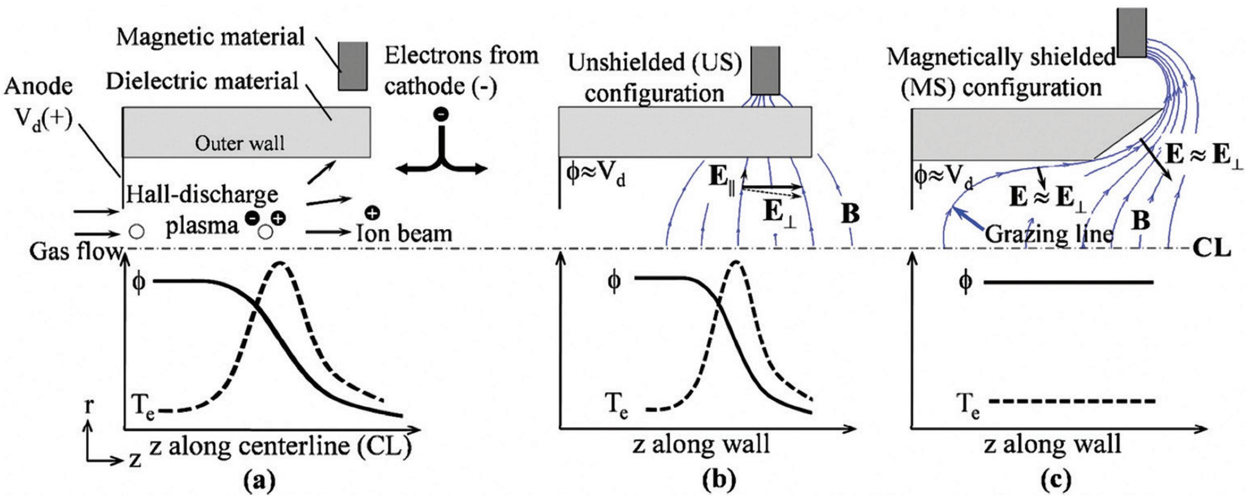

Figure 3. Schematics of the different structure of HTs (top) the potential (ϕ) and the electron temperature (*Te*) distribution along the center line. From left to right are traditional configuration, US configuration, and MS configuration, respectively.

Furthermore, the momentum equation of electrons can be simplified as

$$E_{//} \approx -T_e \nabla_{//} \ln n_e \tag{2}$$

and the resistive contribution to the electric field is negligibly small. Eqs. (1) and (2) contribute to two important properties of the force lines in HTs [15], that is, $T_e \approx T_{e0}$ and $\phi \approx \phi_0 + T_{e0} \ln(n_e/n_{e0})$ along a magnetic field lines, where T_{e0}, ϕ_0, and n_{e0} denote integration constants.

As shown in **Figure 3**, the MS configuration can be obtained by optimizing the magnetic field to realize a higher potential ϕ and a lower Te near the cavity surface. The parameter Te has its lowest value when the electrons are closet to the discharge voltage Vd, such that the kinetic energy of the injected ions and the sheath energy are reduced to values near or below the sputtering yield threshold. In addition, if the magnetic field is designed to appropriately match with the geometry of the discharge channel, the generated self-consistent electric field will be larger, and the field direction will be approximately perpendicular to the channel.

Therefore, the main principle when designing MS HTs is to recognize that the pressure of the electrons (yielding $T_e \times \ln(n_e)$ in Eq. (2)) is such that the electric field E is no longer orthogonal to the magnetic field, which can be clearly observed in **Figure 3**. Hence, if the magnetic field lines with convex curvature toward the anode [16] near the channel walls are not equipotential, then they are not able to effectively control the near-wall electric field.

These aforementioned ideas are consistent and provide some interesting insight into the theoretical development of magnetic shielding technology. The design of the H6MS Hall thruster in particular is based on this technological innovation [17, 18]. **Figure 4** (left) shows a photograph of the H6MS Hall thruster and its physical condition after operating continuously for 15 h. JPL demonstrated, using both numerical simulations and experiments, that the ion beam produced in a US HT can be controlled effectively, and the erosion rate on the walls is decreased by 2–3 orders [19].

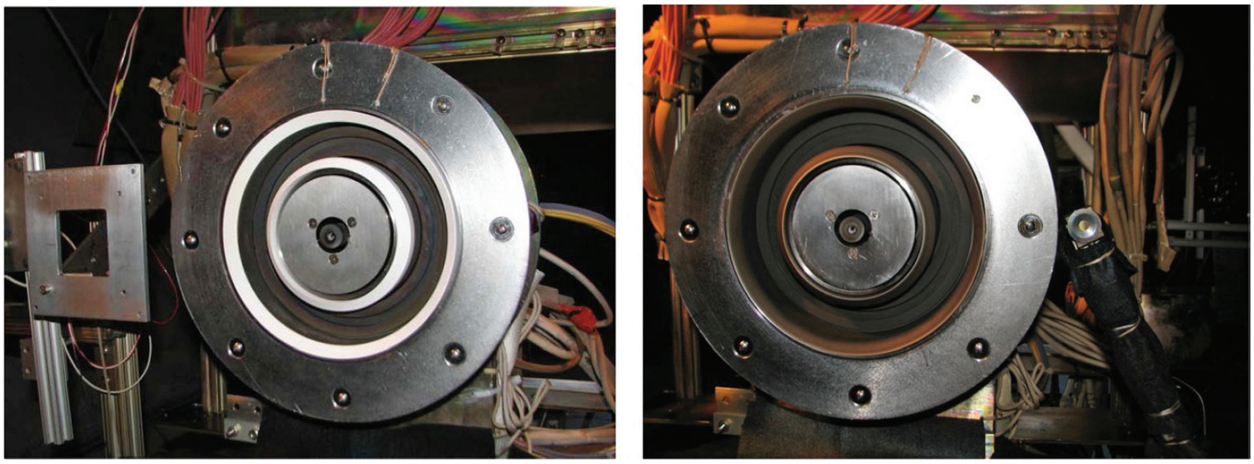

Figure 4. H6MS Hall thruster before (left) and after (right) 15 h of testing. The ceramic walls were covered with a carbon film which was back-sputtered from the vacuum device's inner wall.

In addition, JPL also applied a magnetic shielding technique to a miniature Hall thruster. This investigation, which was performed with the cooperation of the University of California, led to the development of a magnetically shielded miniature HT (MaSMi HT), which was operated with a 275 V discharge voltage and a 325 W discharge power [20]. In Europe, CNRS (France) also realized a magnetic shielding technique for Hall thrusters which operated at a discharge power of 1.5 kW (200 W–PPS-flex and ISCT200-MS Hall thruster) [9, 21].

4. Wall-less technology

The relatively short lifetime of HTs due to plasma-surface interactions inside the discharge chamber is another drawback of conventional Hall thrusters. The underlying cause of this problem is channel wall erosion caused by the bombardment of high-energy electrons and ions. It is known that the choice of material of the channel wall influences the properties of the plasma discharge dynamics, which consequently influences the performance and the lifetime of the thruster. The plasma properties in a Hall thruster are also influenced by the secondary electron emission of the wall material.

Wall-less Hall thruster (WL-HT) was proposed to reduce the interaction between plasma and Hall thruster's channel walls. The objective is to limit the plasma-wall interaction by moving the ionization and acceleration regions to the exterior of the discharge channel. Such an unusual configuration was first proposed by Kapulkin et al. of Russia, during the 1990s. The concept was then proposed based on the idea of a Hall thruster, with an external electric field. Nevertheless, the assumption that limitations of the ion current are linked to the plasma instabilities led researchers to transition from a standard one-stage structure to a two-stage structure. However, the concept of a two-stage structure is less attractive because of its complicated design and operation. The concept of moving the electric field to the exterior of the channel was also investigated in Russia at TsNIIMASH, for thrusters with anode layer (TAL) in the late 1990s and early 2000s. The researchers demonstrated the possibility of stable operation at a high voltage with a high efficiency [22].

Figure 5 depicts the standard configuration of a conventional Hall thruster and a wall-less Hall thruster. The anode/gas distributor is usually positioned at the bottom of the discharge channel. The cathode is located on the outside of the channel and is the source of electrons for discharge balancing and neutralization of the ion beam in the plume area. A radial directed magnetic field with a bell-shaped intensity distribution along the center line is generally by coils or permanent magnets. As shown in **Figure 5**, the peak value of the magnetic field intensity is typically located near the discharge channel outlet. The ceramic channel constrains the propellant and thus maintains a higher atom density for subsequent ionization processes. The easiest way to move the ionization and the acceleration regions out of the discharge channel is to place the anode directly at the channel outlet plane, which is shown in **Figure 5**. This requires that the shape and size of the channel, as well as the magnetic field topology and discharge channel geometry, are unchanged. The proposed idea is the simplest way to transform Hall thrusters into WL-HTs.

Figure 6 depicts images of a low-power ion source working with Xenon propellant in the standard 200 W-class Hall thruster and WL configuration with a ring anode. The discharge voltage is 200 V, and the propellant mass flow rate (MFR) is 1 mg/s. The photograph with bright light near the channel exit (right) indicates that the discharge region was pushed outside the ceramic channel, as expected in the WL configuration. A distinct difference between the two methods is that the boundary of the ion beam with WL configuration is less distinct, which means that the divergence angle of the plume region in a wall-less configuration is much larger. The discharge current is also higher for WL compared to the standard configuration. Therefore, the thruster's performance will diminish and the erosion of external parts, such as the pole pieces, will be increased with time. Moreover, a large beam divergence means that the plasma from thrusters will have a negative effect on the spacecraft elements [23].

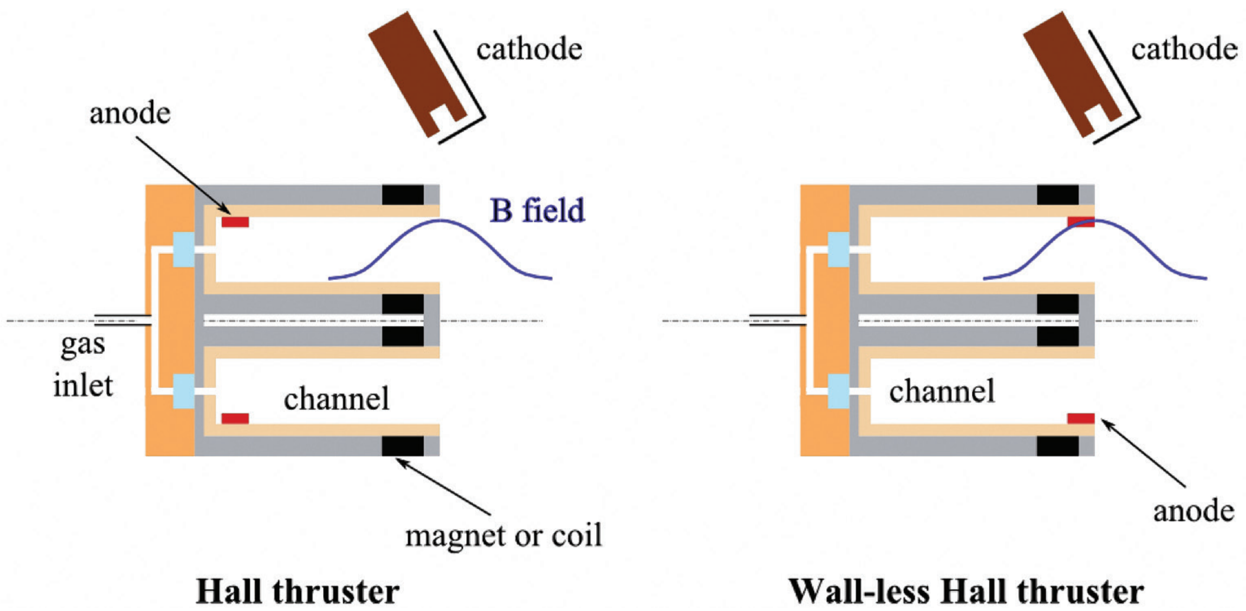

Figure 5. Configurations of a standard Hall thruster and wall-less Hall thruster.

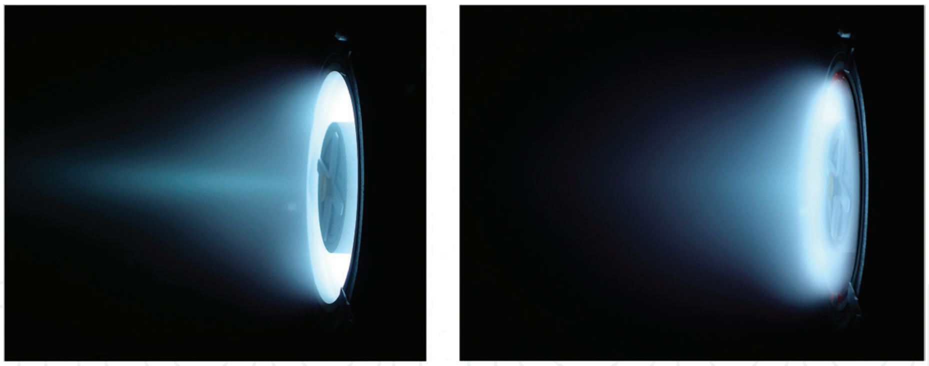

Figure 6. Photographs of the low-power PPI Hall thruster operating at the voltage of 200 V and a MFR of 1 mg/s in standard (left) and WLHT (right) configurations.

Figure 7 displays the interaction between the annular anode and the B-field lines. The magnetic circuit of the original WL-HT prototype, as shown in **Figure 7** (left), is based on the classical Hall thruster design. By shifting the anode from the bottom, to the channel outlet without any other changes, the magnetic field lines are roughly perpendicular to the ceramic wall and intersect with the anode located near the cavity outlet. This results in a decline in the efficiency of the electron confinement. Moreover, a large number of high-energy electrons emitted from the cathode will be trapped along the magnetic field lines and eventually arrive at the anode. Therefore, the electron current is relatively large, and the propellant utilization is low [24].

To solve the problem of excessive energy losses of the electrons at the anode, some optimized prototypes were proposed. The first optimization approach involves rotating the anode by 90 degrees to restore the magnetic barrier, while maintaining the topology of the magnetic field. However, this design does not perform satisfactorily due to two limitations. The first is that a large component of the magnetic field lines near the channel exit does not contribute to the trapping of electrons and the production of thrust. The other is that the ionization and acceleration region are too short for effective electron-atom collision. **Figure 7** (right) portrays a generally satisfactory design. The magnetic field lines are injected axially, and the peak of the magnetic field intensity is pushed downstream at the channel exit. The

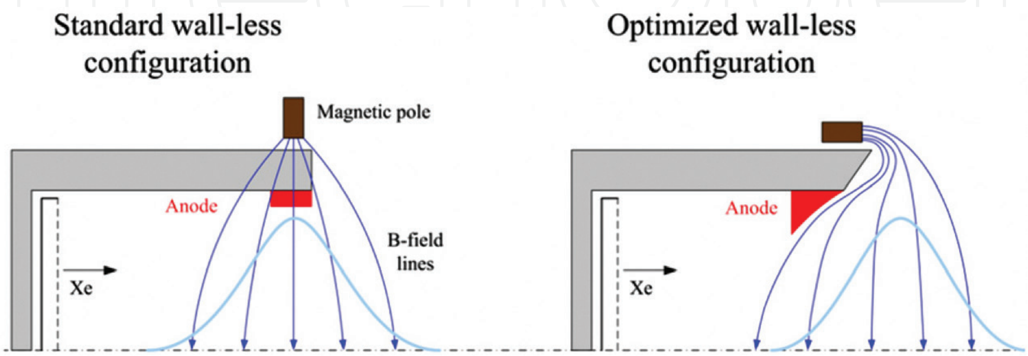

Figure 7. Schematics of original (left) and optimized (right) WL-HT prototype.

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curved anode located at the exit is shaped so that it does not intersect with the field lines, which ensures that the magnetic field can trap electrons and effectively produce thrust. This type of optimization may appear similar to the MS Hall thruster, but the most striking difference is that it is not necessary for the field lines in the WL magnetic configuration to extend deep into the cavity to capture electrons. Therefore, it is quite easy to generate the required magnetic circuit.

Based on the 1.5-kW PPS-Flex HT, some experiments have also been performed. As expected, the discharge current is significantly reduced by the adjustment of the magnetic topology, and the positioning of the anode in parallel. In order to improve the utilization of propellant and achieve a satisfactory specific impulse, thrust level, and anode efficiency, the thruster was operated with a voltage of 500 V. However, the current magnetic does not allow the generation of WL topology with a peak magnetic field value above 90 G. This significantly impacts the operation at high voltage, and further optimization is necessary to reduce discharge current oscillations and increase the thruster efficiency. An improved Hall thruster based on PPS-Flex, which is capable of forming a stronger magnetic field intensity, is currently under development. The influence of the ceramic channel length of the thruster is an important factor that requires further study. It is possible that the channel length may be reduced as ionization takes place near the channel outlet plane. However, it should also be kept sufficiently long to ensure the homogenization of neutral gas.

Another proposed WL prototype was also based on the structure of the PPI thruster. To facilitate more effective and uniform distribution of the xenon gas, a 3-mm-thick gridded anode which covers the channel exit was designed, as shown in **Figure 4**. In order to limit the plasma diffusion in the discharge channel, the width of the anode was decreased. The gridded anode has a transparency of 68% with a 3-mm-diameter hole. Apart from the anode design, the second prototype is almost identical to the first one (**Figure 8**).

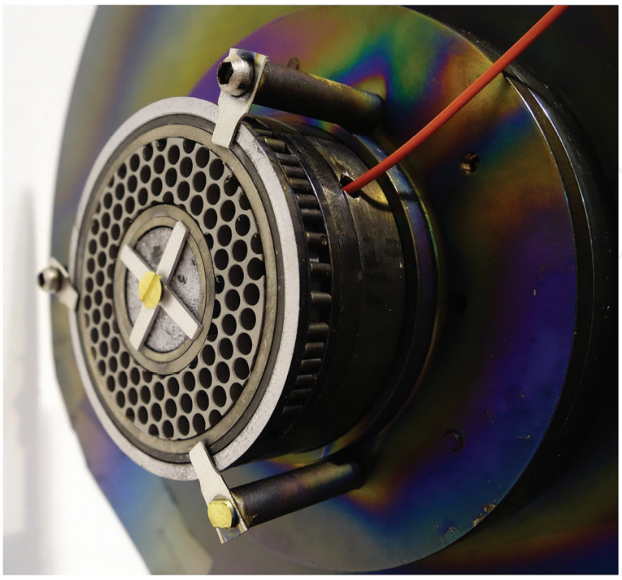

Figure 8. Photograph of the second wall-less thruster prototype with a gridded anode at the exit plane.

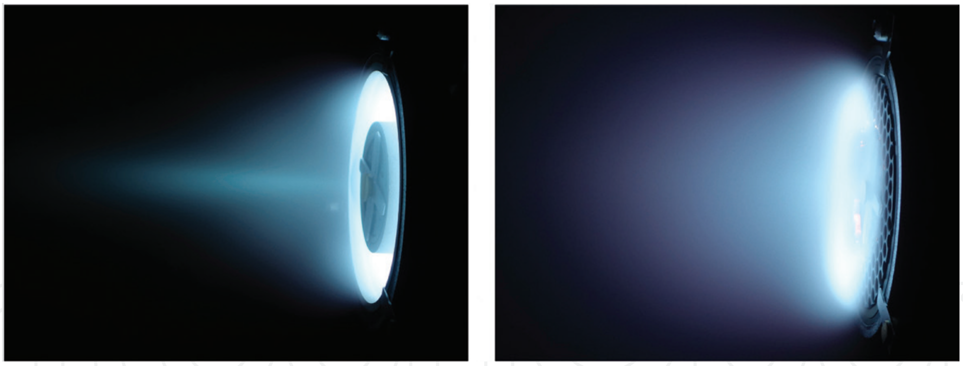

Figure 9. (Left) Photograph of the low-power PPI Hall thruster in standard configuration firing with Xe at 200 V and 1 mg/s. (Right) Photograph of the second prototype of WL-HT with a gridded anode firing with Xe under same conditions.

Figure 9 shows two plume region photographs of the PPI thruster operating with a Xe propellant; the left photograph shows the thruster in a standard configuration, and the right one is the wall-less Hall thruster with a gridded anode. The discharge voltage is 200 V, and the MFR is 1 mg/s. Compared to the anode ring, the discharge area of the Hall thruster with the gridded anode is repositioned outside the discharge channel, which is indicated by the bright light in front of the outlet. The ion beam boundaries of the WL Hall thruster are also less defined in this prototype, which implies that there is a degradation in performance.

Hall thrusters in WL configuration generally experience significant benefit in integration, lifetime, operating envelope, and propellant options. Since the acceleration zone is outside the discharge channel, the channel wall can be substantially shortened, thus reducing the mass and improving the economy of volume. The interaction between the plasma and the walls is also significantly reduced. Therefore, the impact of the channel material on the thrusters' performance is reduced. More importantly, it is presumably possible for the thruster to operate at a higher voltage and with an extended lifetime. In addition, the reduction of the plasma-wall interaction can lead to higher electron temperatures and positive points, which should result in efficient ionization of the propellants such as krypton and argon.

5. Aft-magnetic field with large gradient technology

To address the problems associated with power losses, and the low lifetime associated with the high surface-to-volume ratio of low power Hall thrusters, Harbin Institute of Technology proposed an aft-magnetic field with large gradient technique. In this approach, the maximum magnetic field strength is located on the outside of the channel with a large gradient. Harbin Institute of Technology developed a Hall thruster using a focused magnetic field of low power, which was excited using only two permanent magnet rings, such that the maximum magnetic field strength is outside the channel (Brexit/Brmax = 0.75 can be achieved). The magnetic field gradient in this configuration is much larger than that of a conventional Hall thruster, which can achieve a value of 20 G/mm [25, 26]. **Figure 10** shows the magnetic structure and configuration of the aft-magnetic field setup.

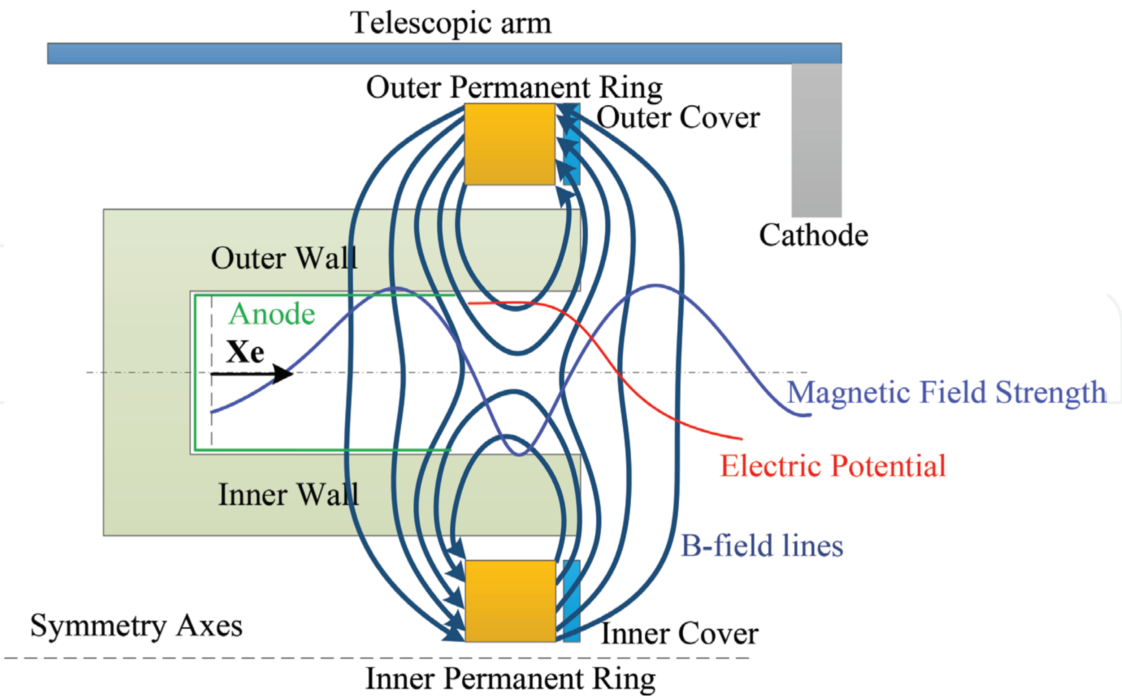

Figure 10. Magnetic structure and configuration.

An approach to push down the magnetic field and the channel can be adjusted accordingly and can achieve plasma discharge without wall loss. The result of calculations based on simulation has confirmed that the abovementioned approach causes acceleration processes to occur outside the channel, but ionization occurs in the channel. The temperature of the walls remains relatively low, since the resulting power deposition on this structure is minimal. This is because the wall is only bombarded with low-energy ions and electrons. Therefore, the channel erosion is effectively reduced, and the operational life of the thruster is extended. In addition, the overall efficiency of the system is improved because additional coil power is not consumed.

Based on this research, Harbin Institute of Technology designed a 200-W Hall thruster with two permanent magnet rings, to facilitate an in-depth investigation of the effects of the aft-magnetic field with a large gradient, on discharge properties and device performance. This thruster has five noteworthy features. First, the magnetic field is only excited by an inner and an outer permanent magnetic ring. Second, the gas distributor and the anode are made of nonmagnetic stainless steel, while the other metal structures of the thruster are made of titanium. Therefore, the other parts of the entire thruster are nonmagnetic, and a magnetic screen is not necessary. Third, the anode's front end-face is at the internal magnetic separatrix position, and it has a hollow structure. Compared to the traditional Hall thrusters, the distance from the channel outlet to the zero-magnetic region is shorter, which implies that the magnetic field gradient is larger than that of traditional Hall thrusters. Fourth, by using various sets of ceramic rings, the channel length can be easily changed while keeping the width of the channel fixed. Finally, 50% of the thruster's shell components are hollow. To effectively reduce the discharge channel temperature, they are directly exposed. References [27, 28] highlight the visual preliminarily evidence, which confirms the feasibility of the proposed thrusters. The thruster is able to discharge with lower wall energy loss and eliminate wall erosion both in a straight channel and in an oblique arrangement (Brexit/Brmax = 0.75). The maximum anode efficiency is 29.1% (straight channel) and 34.2% (oblique channel) with a discharge power of 200 W. When the channel is enlarged to Brexit/Brmax = 0.9, the anode efficiency can be improved to 42% [27]. **Figure 11** depicts photographs of the ceramic channel after a discharge with Brexit/Brmax = 0.75. It is observed that there is a 1-mm-long area, which is slightly yellow, in the outlet area of the inner ceramic wall. A black deposition is also observed, which almost completely covers the entire outer ceramic wall. Neither of these observations indicate that the whiteness of the ceramic bottom is caused by a bombardment of high-energy ions. It can therefore be concluded that there are very few high-energy ions which bombard the wall and cause erosion. The resulting ions are mainly low-energy ions [26].

In order to extend the life and improve the performance of low-power Hall thrusters, Harbin Institute of Technology has done further research on anode design [29–31] and channel wall material analysis [32].

Unlike conventional Hall thrusters, the peak of the magnetic field strength is outside the discharge channel, for Hall thrusters which adopt an aft-magnetic field with a large gradient and double peak. Therefore, the distance from the channel outlet to the zero magnetic field region is relatively short. However, if the thruster adopts a traditional anode configuration and anode location, it will experience a drop in its performance, as this configuration may cause an inadequate homogenization of neutral gas. Hence, a comparative study was performed for a U-shaped hollow anode with the front end-face and the flat plate anodes in the zero magnetic field region, with the first magnetic peak (corresponding to the rear and front end-faces of the U-shaped anode, respectively). The research shows that under the same operating conditions, the highest overall performance is achieved for thrusters with a hollow anode. For an anode positioned at the magnetic peak, its ionization rate is at a maximum. However, most of the ionized ions produced bombarded the walls, resulting in energy loss and reduced performance. For an anode in the zero magnetic field region, the voltage and propellant utilization are lower than those of the hollow anode. Thus, although the maximum ionization rate is higher than that of the hollow anode, the wall power loss is slightly smaller. In addition, due to its shorter ionization region and relatively shorter channel, it also has a poor overall performance compared to that of the hollow anode [28].

Figure 11. Ceramics rings after discharge.

Due to the large gradient of the magnetic field, matching the magnetic field to the anode's position is very important, which when carried out to a very large extent determines the performance of the thruster. Simulation and experimental results demonstrate that when the anode is placed between the outer and inner magnetic separatrices, both the efficiency and the thrust are at a maximum. The significant energy losses on the walls result in a low efficiency and thrust, despite the high degree of ionization, when the anode is placed at the inner magnetic separatrix. Thus, the performance of the thruster is at its lowest when the anode is at the outer magnetic separatrix, because of the lower ionization level and larger divergence angle of the plume, as the ionization zone is shifted toward the plume region [24].

A hollow indented anode is proposed to increase the neutral gas density in the discharge channel, so that the performance of the thruster can be improved. The experimental results to date indicate that this structure can effectively improve the performance (in terms of anode efficiency, ionization rate, propellant utilization, and thrust) compared to the hollow straight anode, under similar operating conditions. Simulation results indicate that the neutral gas density can be effectively increased by the utilization of an indented anode in a discharge channel and on the centerline of the channel. Furthermore, the ionization rate in the channel and the preionization in the anode can also be increased. Therefore, the hollow indented anode can be considered as an important design concept for improving the thruster's performance [30].

As acceleration occurs in the plume area and ionization occurs in the channel, the simulation and experimental results indicate that the maximum electron temperature can be found in the plume zone, while the electron temperature in the channel is relatively low. The secondary electron emission yield of the channel material will have a small but measurable effect on the thruster's performance. This assertion was experimentally verified. It was confirmed that materials with low sputtering yield could be used to further increase the life of the low-power thrusters while discharging through a channel with walls of titanium and graphite. **Figure 12** shows a picture of the 200-W prototype Hall thruster and plume discharge with titanium wall material [31].

Two additional low-power Hall thrusters were designed by Harbin Institute of Technology, with power ratings of 10–20 W and 50–100 W. The maximum anode efficiency was about 30%,

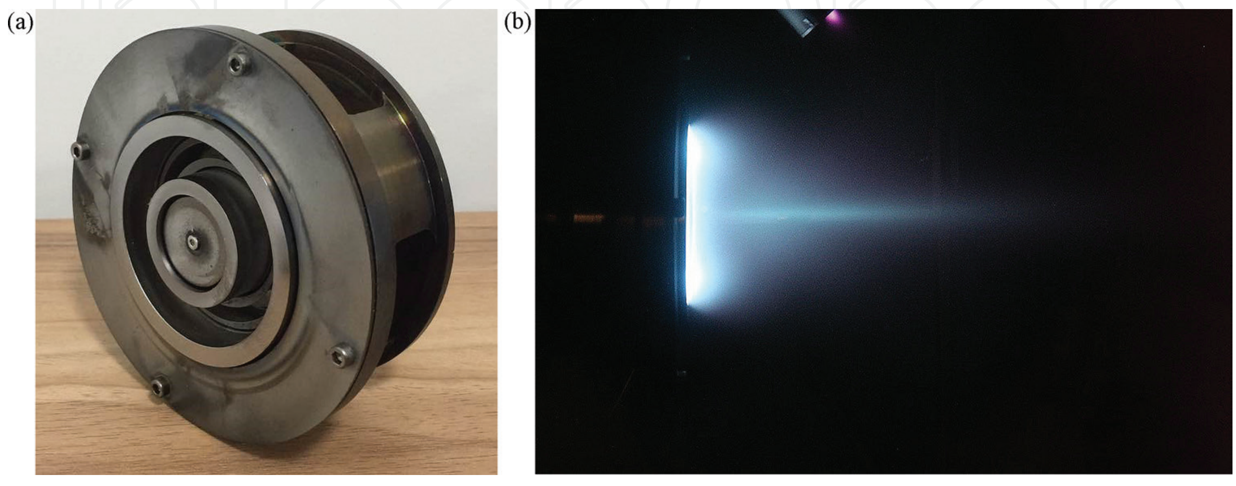

Figure 12. 200 W Hall thruster discharge with titanium wall material (a) prototype of the Hall thruster and (b) picture of discharge plume.

when the design was based on an aft-magnetic field with large gradient technique. High-power thrusters which operate at 1.35 and 5 kW have been designed and tested at the Harbin Institute of Technology using the aft-magnetic field with large gradient technique. The maximum efficiency attained was 65%. Therefore, the aft-magnetic field with large gradient technique can be widely used in Hall thrusters to achieve different power outputs.

6. Outstanding problems

The purpose of the MS technology is to facilitate the equipotentialization of the near-wall magnetic field lines. The topology of these lines reaches deeply into the near anode region and eliminates the influence on the potential originating from electron pressure. On the basis of the isothermal principle of magnetic field lines, $E_{//}$ is negligibly small. Meanwhile, the induced $E\perp$ prevents ion bombardment of the ceramic walls, which significantly reduces channel erosion. Nevertheless, there are still two primary problems that need to be addressed: (1) the large excitation power consumption and the relatively low thruster efficiency. As a result, an additional component for heat dissipation is required, especially for low-power HTs; (2) Ioannis et al. [33–35] first discovered that the pole erosion of the magnetic shield of Hall thrusters is a by-product of magnetic shielding. Although the erosion rate is small, it will affect the lifetime of thrusters over long periods of time.

The wall-less technology involves moving the anode to the channel exit, which entirely shifts the ionization and acceleration region to the outside of the channel defined by the wall-less Hall thrusters. The ionization of neutrals occurs in the plume region, where the neutrals spread radially without the control of the channel wall, thus resulting in a larger plume divergence (55°–62°). Thus, the performance of this device is relatively lower.

The aft-magnetic field with large gradient technique causes the maximum magnetic field strength to be generated on the outside of the channel with a large gradient. Primary ionization can be maintained inside the channel, and the primary acceleration can be directed toward the plume region, which can maintain a high level of propellant utilization while decreasing the energy, flux of electrons, and the ions that bombard the ceramic channel wall. In the future, the channel and the magnetic field should be the two main considerations while attempting to optimize the discharge performance of HTs. In addition, the coupling of the cathode with the thrusters should be studied.

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Conflict of interest

This chapter has no conflicts of interest.

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