

# Hall Thruster Modifications for Reduced Power Operation

IEPC-2005-080

Presented at the 29<sup>th</sup> International Electric Propulsion Conference, Princeton University,  
October 31 – November 4, 2005

J. Ashkenazy\*, S. Shitrit<sup>†</sup> and G. Appelbaum<sup>‡</sup>

*Propulsion Physics Laboratory, Soreq NRC, Yavne 81800, ISRAEL*

**Abstract:** The problems and limitations of Hall thruster operation at power levels below 300 Watts are reviewed and analyzed. The most critical problem seems to be the sharp drop in the expected operating lifetime of down-sized thrusters. As a consequence, the approach taken here is to look for modifications of larger thrusters, that can effectively improve the propellant utilization and, as a result, the overall performance at the reduced power levels. Limited improvements are obtained by channel length extension in the 200-300 Watts range. Preliminary results with a reversed magnetic field profile provide an encouraging indication for a better focusing of the ions.

## Nomenclature

$B, E$  = magnetic, electric field  
 $e$  = electron charge  
 $h$  = channel width  
 $h_c$  = channel wall thickness  
 $I_d, I_i, I_c$  = discharge, ion, coil's current  
 $I_{sp}$  = specific impulse  
 $L$  = channel length  
 $l_a$  = effective acceleration length  
 $m$  = mass of xenon atom  
 $\dot{m}$  = propellant mass flow rate  
 $M_0, M_{fuel}$  = spacecraft empty mass, fuel mass  
 $n_e$  = electron density  
 $N$  = coil's turns  
 $r_m$  = average channel radius  
 $v_e, v_i, v_a$  = electron, ion, neutral velocity  
 $V_d$  = discharge voltage  
 $S$  = channel cross-sectional area  
 $t_{life}$  = thruster operating lifetime  
 $\lambda_i$  = characteristic ionization length  
 $\sigma_i$  = ionization cross-section  
 $\eta_T$  = thruster efficiency  
 $\eta_p, \eta_v$  = propellant, voltage utilization  
 $\eta_i$  = current ratio  
 $\Phi$  = magnetic flux  
 $\mathfrak{R}_g$  = gap reluctance

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\* Head of electric propulsion group, joseph@soreq.gov.il

<sup>†</sup> Graduate student

<sup>‡</sup> Research assistant

## I. Introduction

As is well known, the main advantage of electric propulsion is the high specific impulse which results in significant savings in propellant mass. These savings could lead to a reduction in mission costs, or to the extension of mission time, or could enable very large  $\Delta v$  missions that cannot be implemented practically with conventional propulsion. At the same time, due to the typical low thrust, electric thrusters are required to have a long operating lifetime, in the thousands of hours level. Small spacecraft and micro-satellites could also benefit from the advantages of electric propulsion in large  $\Delta v$  missions provided that high performance can be obtained under the constraints of limited power and propulsion system dry mass and for the required long operating time. Among the various electric propulsion options, Hall thrusters represent by now a mature technology that have demonstrated high specific impulse and efficiency values in a broad power range, from sub-kilowatt level and up to a few tens of kilowatt. However, at power levels of 300 Watts and below, the performance of Hall thrusters tends to degrade. This problem is even more severe when the operating lifetime is considered.

The problems and limitations of Hall thrusters at low power levels are reviewed in section II. The typical drop in the performance of a given Hall thruster when the power is reduced<sup>1-3</sup> was already shown to be a result of the reduction in ionization efficiency when the mass flow is decreased<sup>2-4</sup>. The straightforward approach to overcome this problem, scaling down, was also addressed in the past and was shown to be eventually limited by magnetic circuit saturation and volume constraints<sup>4</sup>. Here, we use a 2D finite-element simulation program and demonstrate that magnetic saturation indeed limits the ability to scale down Hall thrusters to the power range below 300 Watts. We address also the lifetime problem and show that, while the operating lifetime of future low power thrusters will be required to be no smaller than that of larger power thrusters, the actual lifetime of down-sized Hall thrusters is expected to drop sharply due to the reduced ceramic thickness, the increased ion current density (in some of the scaling schemes), and the above mentioned magnetic saturation problem.

Due to the problems and difficulties associated with the scale down approach, we have adopted a different approach for Hall thrusters in the 200–300 Watts power range of trying to improve the propellant utilization of an existing thruster by modification of its configuration without scaling it down. A straightforward implementation of this approach is channel extension. Past experiments have already demonstrated that this type of modification can improve thruster performance at reduced mass flows<sup>2-4</sup>. The present experiments focused on trying to improve the performance of a 600 Watts thruster at the 200-300 Watts power range. The results of these experiments indicated that while performance improvements can be obtained at this power range by channel extension, the improvements are limited. These results are summarized in section III. Another modification, described in section IV, is to apply near the anode a magnetic field with a sign opposite to that of the field near the channel exit. The higher magnetic field strength near the anode is expected to result in an increase in the electron density and hence in the ionization rate in that region. At the same time, the higher gradient magnetic field profile could result also in a better focusing of the accelerated ions compared to the "classic" profile of SPT-like thrusters. A modified magnetic circuit was developed which enabled to obtain a reversed field near the anode with a minimal degradation of the near exit field. Preliminary thruster operation results provided an encouraging indication for a better focusing of the ions.

## II. Problems and Limitations of Hall Thrusters at Power Levels below 300 Watts

### A. The Propellant Utilization Problem

The operating power of a specific Hall thruster can be reduced by lowering either the discharge voltage,  $V_d$ , or the discharge current,  $I_d$ . However, thruster operation at a reduced voltage results obviously in a lower ion energy and hence a decreased specific impulse. Thus, the more favorable approach is to keep the discharge voltage fixed and to reduce the discharge current by reducing the propellant mass flow rate. However, as has been demonstrated many times, for example in Refs. 1-4, decreasing the mass flow rate of a given Hall thruster configuration results in reduced thruster efficiency and specific impulse. This behavior is due to the decrease in the propellant utilization, which both the efficiency and the specific impulse are proportional to, as the mass flow rate is reduced. To see that we note that the characteristic ionization length can be written as<sup>4</sup>:

$$\lambda_i = \frac{v_a}{n_e \langle \sigma_i v_e \rangle} = \frac{m v_a v_i}{\eta_p \langle \sigma_i v_e \rangle \dot{m}}, \quad (1)$$

where  $n_e$  and  $v_e$  are respectively the electron density and velocity,  $v_a$  and  $v_i$  are respectively the neutral and ion velocities,  $\sigma_i$  is the ionization cross section,  $m$  is the xenon atom mass,  $S$  is the thruster channel cross-sectional area,  $\dot{m}$  is the propellant mass flow rate, and  $\eta_p$  is the propellant utilization defined as the ratio of the ion flow rate at the thruster exit to  $\dot{m}$ . In deriving the right side of Eq. (1) use was made of the quasi-neutrality condition. As we can see, even if we assume at first that the propellant utilization is unchanged, decreasing the mass flow rate results in an increase in  $\lambda_i$  which leads to a reduction in the ionization rate and as a result also in the propellant utilization.

## B. Scaling Down and Magnetic Circuit Limitations

A straightforward approach to overcome the propellant utilization problem is to scale down the channel cross-sectional area with the mass flow rate, i.e.,  $S \sim \dot{m}$ . In this case the length of the channel,  $L$ , is unchanged while the channel average radius,  $r_m$ , and width,  $h$ , scale as the square root of the mass flow, i.e.,  $r_m, h \sim \dot{m}^{1/2}$ . Eq. (1) indicates that in such a "cross-sectional" or "radial" scaling the ratio of the characteristic ionization length to the channel length is unchanged<sup>4</sup>,  $\lambda_i/L \rightarrow \lambda_i/L$ . However, this scaling scheme has a drawback since the propellant utilization is affected also by recombination at the channel wall, which depends on the ratio  $h/L$ . Wall recombination is expected then to increase in the narrowed channel resulting in some degradation of the propellant utilization.

Another scaling scheme is the "photographic" scaling<sup>5</sup>, called also "ideal" scaling<sup>6</sup>, in which all the linear dimensions are scaled with the mass flow, i.e.,  $r_m, h, L \sim \dot{m}$ , while  $S \sim \dot{m}^2$ . From Eq. (1) it follows also that  $\lambda_i \sim \dot{m}$ . Therefore we get  $\lambda_i/L \rightarrow \lambda_i/L$  and  $h/L \rightarrow h/L$ , i.e., both the ratio affecting ionization and the ratio affecting wall recombination are conserved!

As is well known, the thruster efficiency can be written as  $\eta_T = \eta_p \eta_v \eta_i$ . The voltage utilization,  $\eta_v$ , is defined as the ratio of the average exit ion energy to  $eV_d$ , while the current ratio,  $\eta_i = I_i/I_d$ , where  $I_i$  is the exit ion current<sup>3</sup>. A successful scaling would require then to restore, in addition to the propellant utilization, the voltage utilization and the current ratio values obtained with the original thruster at the higher power. The voltage utilization is determined, to large extent, by ion energy losses due to wall collisions at the region near the exit were most of the voltage drop and hence most of the acceleration takes place. These losses are indeed affected by the angle by which the ions "see" the thruster exit, which goes as  $h/l_a$ , where  $l_a$  is the effective length of the accelerating region which is controlled by the width of the magnetic field profile. Another effect by which energy wall losses are affected by the accelerating region geometry is the radial electric field that results from the electron pressure gradient<sup>4</sup>,  $E_r \approx kT_e/eh$ , which pushes the ions towards the walls. When compared to the axial accelerating voltage,  $E_z \approx V_a/l_a$  (the accelerating voltage,  $V_a$ , has a value somewhat smaller than  $V_d$ ), we see that the ratio  $E_z/E_r$  also goes as  $h/l_a$ . It is clear then that in order to avoid an increase in ion energy losses  $l_a$  must scale with the channel width, i.e.,  $l_a \sim h \sim r_m$ .

Using the quasi-neutrality relation the current ratio can be written as  $\eta_i = (1+v_e/v_i)^{-1}$ , where  $v_e$  and  $v_i$  are respectively the electron and ion axial velocities. While the ion velocity is proportional to the square root of the voltage, the axial electron velocity can be written as  $v_e \approx \mu_\perp V_a/l_a$ , where  $\mu_\perp$  is the electron mobility across the magnetic field for which we take the Bohm mobility<sup>7</sup>,  $\mu_\perp \sim B^{-1}$ . We see then that the ratio of electron to ion velocities goes as  $V_a^{1/2}/Bl_a$ . From which follows that at a constant operating voltage the magnetic field strength has to scale as the inverse of the effective acceleration length in order to conserve the current ratio when the thruster is scaled down, i.e.,  $B \sim 1/l_a \sim 1/h \sim 1/r_m$ .

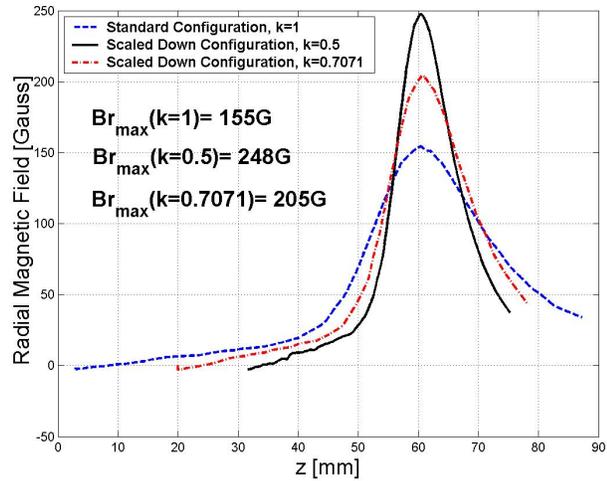
Let us refer to a simplified magnetic circuit composed of a magnetic coil, an iron core, and pole pieces forming a gap around the accelerating region. The magnetic flux,  $\Phi \approx 2\pi r_m l_a B$ , then scales as  $r_m$ . Assuming that the radius of the iron core is scaled as  $r_m$  and taking into account flux conservation, we get that the magnetic field strength in the core,  $B_i \sim 1/r_m$ . That is to say, as the thruster is scaled down the magnetic field strength inside the iron core has to increase and eventually it will reach saturation. This problem depends on the B-H curve of the core material and hence could be more severe at the elevated temperatures during thruster operation. It leads to flux losses and distortion of the magnetic field distribution and, as a results, could prevent from the down-sized thruster to obtain the effective accelerating length and/or magnetic field strength required by the scaling rules presented above.

In principle, the saturation problem could be partially avoided if the cross-sectional area of some of the iron core parts, those which do not directly affect the field distribution, are scaled down only as  $r_m$  or less. In this case we will have  $B_i \sim \text{constant}$  inside these parts. However, this approach is limited by the available volume, especially at the thruster center, when the channel is scaled down. The problem of available volume becomes more severe when we consider also the coils. To see that let us refer again to the above mentioned simplified magnetic circuit whose equation can be approximated by  $NI_c \approx \mathfrak{R}_g \Phi$ , where  $N$  is the number of coil turns,  $I_c$  is the coil current., and  $\mathfrak{R}_g \approx$

$h/(2\pi\mu_0 l_a r_m)$  is the gap reluctance. The reluctance of the iron core is negligible compared to  $\mathfrak{R}_g$  since the iron permeability  $\mu \gg 1$ . Since  $\Phi \sim r_m$  and  $\mathfrak{R}_g \sim 1/r_m$  it follows that  $NI_c$  has to remain constant as the thruster is scaled down and the available volume diminishes. Trying to avoid this problem by increasing the coil current on the expense of  $N$  could result in increased power dissipation in the coils leading to a reduced overall efficiency and increased heat load problem. The increased coil current could result in additional penalty in terms of added mass and volume of the coil power supply. Another approach is to avoid the use of internal coils. However, this requires to simplify the magnetic circuit topology and would result in a compromise in the ability to control the magnetic field distribution and in particular  $l_a$ .

The dimensional analysis above has demonstrated that in general the scale down approach is eventually limited by saturation problems and volume constraints. Nevertheless, since our present interest is in 200-300 Watts thrusters, it is important to verify whether these problems are already encountered in this power range. For that purpose we used a 2D finite-element simulation to compare the magnetic circuit of a thruster with  $r_m = 28\text{mm}$ , which was designed to operate at 600 Watts, with the same magnetic circuit scaled down by a factor of  $0.5^{1/2}$ , which roughly corresponds to a "cross-sectional" scaling to a 300 Watts thruster ( $r_m \approx 20\text{mm}$ ), and by a factor of 0.5, which corresponds to a "photographic" scaling to a 300 Watts thruster ( $r_m = 14\text{mm}$ ). The simulated magnetic circuit consists of internal and external pole pieces and screens, internal and external core rods, and a back plate, all made of low carbon steel ("soft iron"), and internal and external magnetic coils. As required by the dimensional analysis, the same value of  $NI_c$  was used in all three simulation cases. By doing so, we disregarded the volume constraints and/or dissipation problems mentioned above. A theoretical B-H curve with a saturation value of  $\sim 18 \text{ KGauss}$  was used in the simulations. The simulated magnetic field distributions along the channel median for the three cases are shown in Fig. 1.

They demonstrate the expected narrowing of the field distribution and increase in field strength as the magnetic circuit is scaled down. However, while the magnetic field strength values are required to scale as  $1:1.4:2$  ( $B \sim 1/r_m$ ), the simulated maximal values, 155, 205 and 248 Gauss, scale as  $1:1.32:1.6$ . For the same three cases, the simulated maximal field values inside the central core rod, 11, 13.5 and 16 KGauss, scale as  $1:1.23:1.45$ . The discrepancies between the simulated and required magnetic scale factors which increase as the geometric scale factor  $k$ , becomes smaller are a result of saturation. They indicate the difficulties in obtaining the required magnetic field strength for scaled down thrusters in the power range below 300 Watts. In reality, with a less ideal B-H curve, and with coil volume constraints and heat loads, these difficulties are expected to be much worse.



**Figure 1. Simulated radial magnetic field along the channel axis for the original ( $k=1$ ) and for two scaled-down configurations,  $k=0.5^{1/2}$  and  $k=0.5$ .**

### C. The Operating Lifetime Problem

While the main advantage of electric propulsion is the very large specific impulse, electric thrusters of all kinds including Hall thrusters are known also to be characterized by their very low thrust. Since a spacecraft propulsion mission is determined by the required total velocity increment,  $\Delta v$ , (or the required total impulse), the low thrust of electric thrusters results in a very long operating time, in the range of thousands of operating hours. Moreover, as it is more beneficial to use electric thrusters in large  $\Delta v$  missions, where the mass saving is large, the demand to extend the operating lifetime of electric thrusters can be expected to continue in the future.

In order to consider what happens to the required operating lifetime,  $t_{life}^* = M_{fuel} / \dot{m}$ , when the onboard power available for thruster operation is reduced, we use the rocket equation,  $M_{fuel} = M_0(e^{\Delta v/g_{sp}} - 1)$ , together with the thruster efficiency,  $\eta_T = \dot{m} g^2 I_{sp}^2 / 2P_e$ , to get:

$$t_{life}^* = \frac{g^2 I_{sp}^2 M_0}{2\eta_T P_c} (e^{\Delta v/gI_{sp}} - 1), \quad (2)$$

where  $M_{fuel}$  is the fuel mass required to accomplish the mission and  $M_0$  is the spacecraft empty mass. As we can see, even if we succeed in obtaining the high performance of higher power thrusters, namely the specific impulse and the efficiency, the reduced onboard power tends to extend the required operating lifetime. Furthermore, even if the reduced power thruster is intended for use onboard a smaller size spacecraft, e.g., a micro-satellite, we still need to keep the same specific power,  $P_c/M_0$ , not a simple task by itself, in order not to extend the required lifetime. To summarize, the operating lifetime of future low power electric thrusters is required to be not smaller, and most probably larger, than that of present and near future higher power thrusters.

While the last paragraph dealt with the required operating lifetime of reduced power thrusters, let us now try to estimate what happens to the actual operating lifetime of scaled down Hall thrusters. First, we note that the erosion of the ceramic channel walls by colliding energetic ions in the acceleration region is usually regarded as the main mechanism of thruster degradation determining the operating lifetime. Generally speaking, the channel erosion rate is proportional to the radial ion flux density,  $\frac{dh_c}{dt} \propto J_{ri}$ , where  $h_c$  is the ceramic wall thickness, and the

proportionality factor is a function relating the effectiveness of erosion by the colliding ions to their kinetic energy, the angle of impact at the wall, and the ceramic material properties. Assuming that the operating conditions are practically unchanged during the mission, the thruster lifetime will be proportional to the initial channel thickness,  $h_{c0}$ , and inversely proportional to the radial ion flux density. If the magnetic field profile and strength are scaled down properly as outlined above, we can further assume the radial ion flux density to be proportional to the ion current density,  $J_{ri} \propto J_i \sim \dot{m}/S$ . Then the thruster operating lifetime,  $t_{life} \sim h_{c0} S / \dot{m}$ . In the case of the "cross-sectional" scaling we have  $S \sim \dot{m}$ , and  $h_{c0} \sim h \sim \dot{m}^{1/2}$ . From which follows that  $t_{life} \sim \dot{m}^{1/2}$ . In the case of the "photographic" scaling we have  $S \sim \dot{m}^2$ , and  $h_{c0} \sim h \sim \dot{m}$ . Then we get  $t_{life} \sim \dot{m}^2$ !

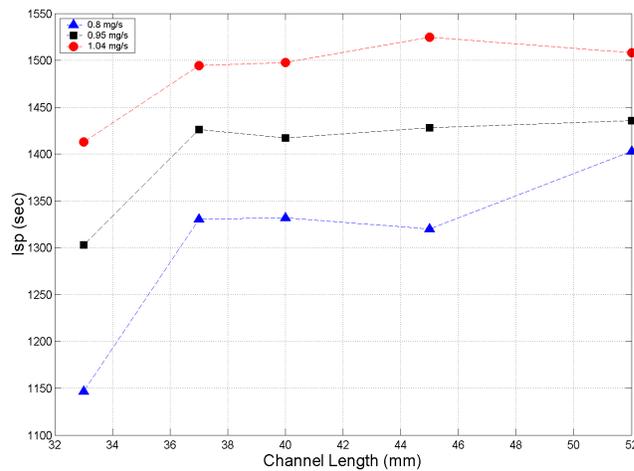
Noting again that at a fixed discharge voltage,  $P_c \sim \dot{m}$ , these results indicate that if we scale for example a 600 Watts thruster with a lifetime of 4000 hours to 300 Watts, its lifetime will be reduced to  $\sim 2800$  hours in the "cross-sectional" case and to only 1000 hours in the "photographic" case! The reduction in the operating lifetime in the scaled down thruster is a result of the reduced ceramic thickness and in the case of the "photographic" scaling also a result of the increased ion current density. While this trend of lifetime reduction, especially in the "photographic" case, already is disappointing, in reality things are expected to be even worse. As discussed above, saturation in the scaled down magnetic circuit core could result in a compromise on the proper scaling of the magnetic field profile and strength and as a consequence in additional wall collisions and heating. Potentially increased dissipation in the coils due to the Ampere-turn limitation and the fact that the ceramic channel walls are thinner in the scaled down thruster could also contribute to the rise in the temperature of the magnetic core and, as a result, to a further enhancement of the saturation problem.

In light of the above discussion it is maybe not surprising that operating lifetime values attributed in the literature to down-sized Hall thrusters in the power range below 300 Watts are in the range of no more than 1000-2000 hours<sup>8-12</sup>, much smaller than that of larger thrusters<sup>13</sup>. Moreover, in most cases these lifetime values are presented as estimations and not as actual results of lifetests. Only in one case<sup>8</sup> we have found a reference to an actual lifetest result: 825 hours for a 325 Watt thruster.

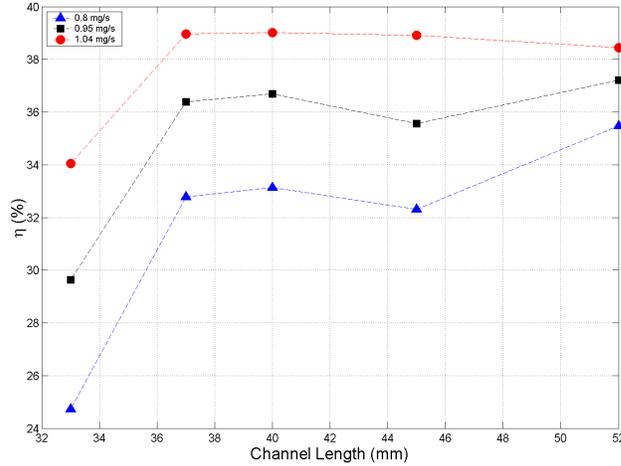
### III. Channel Length Extension

Due to the problems and difficulties associated with the scale down approach and in particular the lifetime problem, we have adopted a different approach for Hall thrusters in the 200–300 Watts power range of trying to improve the propellant utilization of an existing thruster, designed to operate around 600 Watts, by modification of its configuration without scaling it down. This approach has the advantage of avoiding the sharp drop in the operating lifetime and maybe even extending it. As we have seen above,  $t_{life} \sim h_{c0} S / \dot{m}$ . In the framework of our approach the channel thickness,  $h_{c0}$ , and the cross-sectional area,  $S$ , are unchanged while the mass flow rate is reduced, leading to a potential increase in the lifetime! Another potential advantage is the shortening in the engineering development process by building on the experience with an existing thruster.

A straightforward implementation of this approach is to extend the channel length as a compensation for the increase in the characteristic ionization length as the mass flow is decreased (see Eq. (1)). Past experiments, have already demonstrated that larger propellant utilization, specific impulse and efficiency values were obtained with a longer channel length as the mass flow/power was reduced<sup>2-4</sup>. Those experiments, which focused mainly on the 400-700 Watts power range, were performed with a laboratory model thruster. The effective channel length of that thruster was varied in the 20-40 mm range by changing the position of the anode inside an elongated channel. Based on those results, it could be assumed that at the power range of 200-300 Watts optimal performance would be obtained at even longer channel. For that purpose we used a newer laboratory model thruster which enabled to extend the effective channel length up to 52 mm. Thruster performances were measured at 5 effective channel lengths: 33, 37, 40, 45 and 52 mm, at various voltage and mass flow values in the 200-350 Watts power range. Figs. 2 and 3 show respectively the measured specific impulse and efficiency versus the channel length at a discharge voltage of 300 Volts and for three mass flow rate values, 0.8, 0.95 and 1.04 mg/s. These mass flow values corresponded approximately to power levels of 205, 260 and 330 Watts respectively, were at each mass flow there were some small variations in the power level between the different length configurations. As can be observed, there are performance improvements as the channel length is increased from 33 to 40 mm. However, when the thruster is further extended only minor performance differences are observed. A possible explanation for this behavior could be that the electron temperature in the added channel region near the anode becomes too low for those electrons to contribute to the ionization. These results indicate that while performance improvements can be obtained by channel extension at the 200-300 Watts range, the improvements are limited.



**Figure 2. Specific impulse versus channel length at a discharge voltage of 300 Volts for 3 values of the mass flow, 0.8, 0.95 and 1.04 mg/s, corresponding to input power levels of approximately 205, 260 and 330 Watts.**

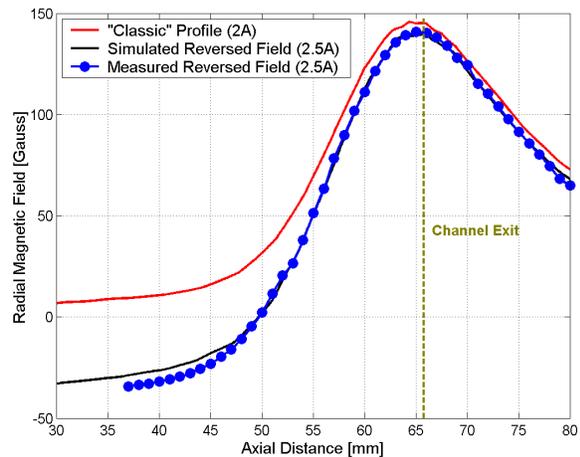


**Figure 3. Thruster efficiency versus channel length at a discharge voltage of 300 Volts for 3 values of the mass flow, 0.8, 0.95 and 1.04 mg/s, corresponding to input power levels of approximately 205, 260 and 330 Watts.**

#### IV. A Magnetic Profile with a Reversed Field near the Anode

Another modification that could improve the propellant utilization is to increase the magnetic field strength near the anode in order to slow the electron axial drift there and by that to increase the electron density and hence the ionization rate (see Eq. (1)) in that region. However, broadening the magnetic field profile could result in a longer acceleration region and a degradation of the focusing of the ion jet, both leading to an increase in ion wall losses and to the corresponding reduced efficiency. In fact, such a modification was tested in our laboratory in the past<sup>14</sup>, and indeed resulted in a reduced performance. In order to overcome this problem, A. Fruchtman<sup>15-16</sup> has suggested to apply near the anode a magnetic field with a sign opposite to that of the field near the channel exit. Such a magnetic field profile has a higher gradient towards the exit. Thus, while it has the potential to improve the ionization near the anode it could result also in a better focusing of the accelerated ions than the "classic" profile of SPT-like Hall thrusters. As a first step in the investigation of the potential of the reversed field profile, a new laboratory thruster had to be designed. The main challenge was to obtain a high gradient profile, which required the magnetic circuit to generate the reversed field near the anode with a minimal degradation of the maximal value of the near exit field. To allow for a study of the dependence of the thruster behavior on the reversed field, it was required also to be able to change its magnitude continuously over a significant range, again with a minimal effect on the near exit field.

Thruster development has been implemented in two stages. First, a modified scheme for the magnetic circuit was found which allowed the penetration of oppositely directed flux to the near anode region with only a moderate impact on the near exit field. The coil's arrangement in this magnetic circuit remained as in the "standard" thruster. A 2D finite-element software package was used in the design and optimization of this magnetic circuit. It was found that only about 25% increase in the coil's current was required compared to the "standard" magnetic circuit in



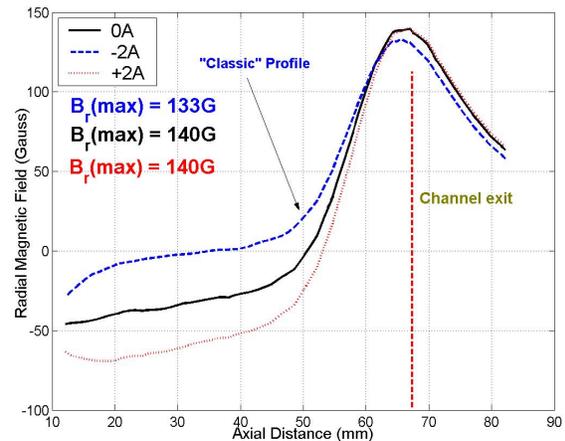
**Figure 4. Simulated and measured field profiles along the channel median of the reversed field thruster (1<sup>st</sup> stage) at a coil's current of 2.5A and a "classic" profile at a coil's current of 2A.**

order to obtain a similar maximal magnetic field strength with the reversed field profile. The magnetic circuit was constructed and its profile measured with a Hall probe. Fig. 4 shows the simulated and measured radial field profiles along the channel median with a coil's current of 2.5A, demonstrating a very good agreement. The maximal radial field near the exit was 140 Gauss. A "classic" field profile obtained with a "standard" magnetic circuit having the same set of coils at a current of 2A is shown also in Fig. 4. As can be seen, a similar maximal radial field is obtained in this case. The effective channel length,  $L$ , is taken from the location of the channel exit backward to the axial position of the anode which can be changed. For  $L = 33$  mm, the radial field at the anode was close to -35 Gauss. It should be noted here that with this first stage modified magnetic circuit the shape of the field profile is fixed and only the magnitude of the field could be changed by varying the coil's current.

A laboratory thruster was assembled with the first stage modified circuit and preliminary thruster operation experiments were performed. The purpose of these experiments was to get a first impression of how a reversed field device behaves as a thruster. In these preliminary experiments the thruster was operated mainly at power levels below 350 Watts, although it was operated also for a short time at up to a power of 600 Watts. The obtained performance level with this fixed reversed field profile and with a channel length of 33 mm followed roughly that of a similar geometry thruster with a "classical" field profile. That is to say, the specific impulse and efficiency values increased with the mass flow rate although they were somewhat below the values obtained with the "classic" field profile thruster. For example, at a power level of 340 Watts the specific impulse and efficiency were 1370s and 32%, as compared to 1410s and 34% obtained with the "classic" profile. Nevertheless, already at this stage there was an encouraging indication for a better focusing of the ions. After a few tens of hours of operation the erosion region (the distinct clean white strip at the channel exit) was about 30% narrower than that obtained with the "classic" profile. This result is maybe due to the sharper gradient of the reversed profile.

In order to study the dependence of thruster performance on the magnitude of the reversed field and to attempt to optimize it, two trim coils were added to the modified magnetic circuit at the second stage of development. The addition of the trim coils enabled us to change continuously the near anode reversed field with a minimal effect on the near exit field. Fig. 5 shows the simulated radial magnetic field profiles for three trim coil's current cases, 2A, 0, -2A. The current through the main coils is 2.5A. As can be seen, a "classic" profile, with a near zero field in the near anode region, is obtained for a trim coil's current of -2A. Raising this current to 2A allows to decrease continuously the near anode field down to a value of about -70 Gauss while the maximal near exit field is changed by only 7 Gauss! Due to volume constraints, the actual trim coils had less turns than in this simulation. As a result, field profiles similar to those shown in Fig. 5 were obtained with a trim coil's current of 2.5A (the main coil's current remained 2.5A).

Initial operation experiments with the second stage reversed field thruster are being performed. In addition to thrust, mass flow and electrical measurements, a combined plume ion flux and heat flux disk probe is used in order to study the effect of the profile on the propellant and voltage utilizations and the current ratio. The probe is mounted on a rotating arm 42 cm from the thruster exit. Operating as an ion flux probe it is negatively biased at  $\approx -30$ V. Integrating over the measured ion flux as a function of the rotating angle gives an estimate for the thruster ion current<sup>2-3</sup>, and hence, with the knowledge of  $I_d$  and the mass flow rate, estimates for  $\eta_p$  and  $\eta_i$ . As a heat flux probe<sup>17-18</sup> it is unbiased. By comparing the probe temperature time derivative when it is immersed in the plume with the temperature time derivative when it is taken out of it, the net heat flux to the probe can be deduced. Integrating over the rotating angle gives then an estimate for the total kinetic power in the emerging jet and hence for the voltage utilization.



**Figure 5. Simulated field profiles along the channel median of the reversed field thruster (2<sup>nd</sup> stage) for a main coil's current of 2.5A and a trim coil's current of -2A, 0, 2A.**

## Acknowledgments

We wish to thank Prof. A Fruchtman, Dr. A. Oren, A. Warshavski, L. Rabinovich and G. Makrinich for fruitful collaborations.

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