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To cite this article: D P Schmidt *et al* 2000 *Plasma Sources Sci. Technol.* **9** 68

Plasma Sources Sci. Technol. **9** (2000) 68–76. Printed in the UK PII: S0963-0252(00)10415-3

A low-power, linear-geometry Hall plasma source with an open electron-drift

D P Schmidt, N B Meezan, W A Hargus Jr and M A Cappelli†

Mechanical Engineering Department, Thermosciences Division, Stanford University, Stanford, CA 94305-3032, USA

Received 30 July 1999, in final form 6 December 1999

Abstract. This paper presents a discussion of the physics of modern Hall plasma thrusters and its impact on the design of new plasma thrusters of varying geometry and power. A particular emphasis is placed on the design and development of a linear-geometry (non-coaxial) source with an open electron-drift current. The operating characteristics of a linear-geometry Hall discharge scaled to operate in the 50 to 100 W power range are presented. Two thruster acceleration channels were fabricated—one of alumina and one of boron nitride. Differences in operation with the two channel materials are attributable to differences in the secondary electron emission properties. In either case, however, operation is achieved despite the lack of a closed electron current drift in the Hall direction, suggesting that there is an anomalous axial electron mobility, due to either plasma fluctuations or collisions with the channel wall. Strong low-frequency oscillations in the discharge current, associated with the depletion of propellant within the discharge, are seen to appear and vary with changes in the applied magnetic field strength. The frequency of this oscillatory mode is higher than that seen in larger (and higher power) discharges, due to the decreased residence time of the propellant within the channel.

1. Introduction

Hall discharge plasma accelerators have been considered for use in satellite propulsion since the early 1960s [1, 2]. In a Hall plasma source, a low-pressure discharge is sustained within a bounded dielectric channel in crossed electric and magnetic fields. Electrons emitted from a cathode external to the channel, or created by the ionization processes, drift along the channel towards the anode located at the channel base. The anode also serves as the source of neutral propellant (typically xenon). The radial component to the magnetic field is designed to be a maximum near the channel exit, and in this region, the electrons become highly magnetized, as the classical electron Hall parameter is much greater than unity. In typical Hall discharge plasma sources, the geometry is co-axial (figure 1) with an annular channel and surrounding solenoids generate a radial magnetic field. In this co-axial configuration, the electrons are constrained to move in the azimuthal direction of the closed $\boldsymbol{E} \times \boldsymbol{B}$ drift, with cross-field drift providing the necessary electron current to sustain the discharge. As the electron Hall parameter is much greater than unity, the Hall current density can be many orders of magnitude greater than the axial current density. According to classical electron transport theory, electrons can circle the annular channel in the Hall direction many times before being captured at the anode. A co-axial geometry therefore allows for this 'closed' electron drift in the Hall direction, and uninterrupted Hall current. The region of trapped electrons acts as a volumetric zone of ionization that in some devices may occupy a small fraction of the overall channel length. The ions generated in this region, unaffected by the magnetic field because of their large inertia, are accelerated by the electric field resulting from the impeded electron flow, producing thrust. Very high ionization fractions and ion velocities can be generated with these discharges and, due to their high efficiencies and high specific impulse, Hall plasma thrusters in the 1–5 kW power range are being evaluated for use on commercial, military and research spacecraft [3].

A precise theory is lacking for the mechanism of cross-field electron transport in Hall plasma thrusters. Early experiments on Hall plasma sources indicated that classical electron transport theory could not account for the measured 'anomalous' axial (cross-field) electron current densities. Janes and Lowder [2] drew attention to the presence of density and electric field fluctuations within the channel of a Hall discharge, and first suggested that these plasma disturbances enhance the axial electron current. Indirect measurements of the 'effective' Hall parameter as a result of these fluctuations were in agreement with the anomalous transport coefficient first identified by Bohm *et al* [4], which characterizes the process now widely recognized as 'anomalous' Bohm diffusion [5]. The Bohm mechanism predicts an electron mobility that scales inversely with the magnetic field strength (as opposed to the classical B^{-2} scaling), and an effective

† Author to whom correspondence should be sent.

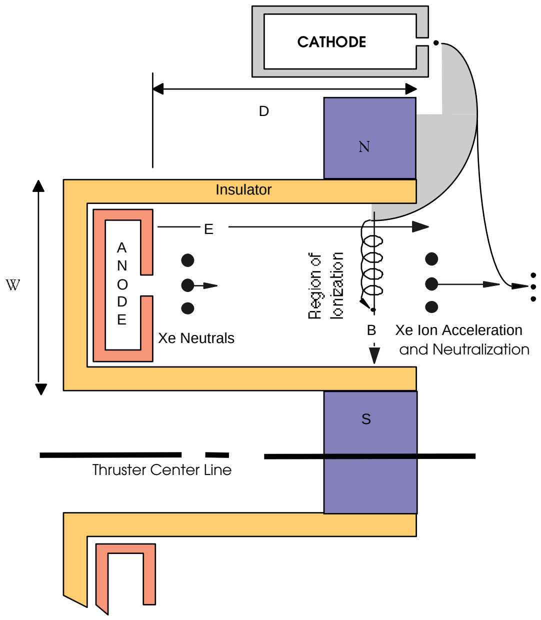

Figure 1. Schematic illustration of a typical co-axial Hall discharge.

electron Hall parameter of about 16. At conditions typical of Hall plasma thrusters near the region where the magnetic field is strongest, the classical Hall parameter is about 500–1000. A value of 16 represents a significant enhancement in the cross-field drift, and indicates that the ratio of Hall current density to axial current density may be much less than that suggested by classical transport theory. While an enhanced electron current due to fluctuations is one possible mechanism for enhanced electron transport, the operation of modern Hall plasma thrusters seems to depend significantly on the properties of the dielectric wall [6]. Previous researchers have proposed the possibility of an enhanced 'near-wall conductivity' due to the 'wall scattering' of electrons. While it seems the precise knowledge of which mechanism is responsible for transport is necessary to properly scale a Hall discharge, we show below that either of these mechanisms exhibits the necessary dependence on discharge parameters to achieve a desired scaling in discharge size or power.

Despite the progress that has been made in the development of co-axial Hall plasma thrusters that operate in the kilowatt power range, a need has developed for low-thrust, high-efficiency propulsion devices to be used for precise orbit control on small, power-limited satellites. A low-power (10–100 W) Hall thruster could fill this need. The proper scaling of a Hall plasma thruster for efficient operation at such low powers requires a renewed examination of the discharge physics that controls thruster performance. Also, alternative geometries that can potentially reduce thruster mass and/or size should be investigated. The scaling of co-axial Hall thrusters to lower powers has been discussed previously in the literature [7, 8]. To our knowledge, however, no one has reported on the operation of a Hall plasma source with a linear geometry and hence an open electron-drift. The merits of a linear-geometry thruster are appealing, although any discharge model based on either classical or 'Bohm' electron transport indicates that even for moderate aspect ratios (depth to channel length ratio, D/L), such a geometry would interrupt the electron Hall current. A linear geometry allows compact packaging of the thruster in a limited space, making the magnetic circuit amenable to the use of permanent magnets. Also, a multiple array of linear thrusters could be efficiently stacked in order to extend the operating envelope of the propulsion system. This modular approach could be used to maintain operation at maximum efficiencies by simply turning stacked low-power linear thrusters on and off as needed to change the thrust level rather than by changing the operating point of a single thruster.

In this paper, we discuss the design and operation of a low-power linear-geometry Hall plasma thruster based on scaling arguments that we have presented previously [8]. The linear thruster tested here is scaled to operate at a power level that is 10–15% that of co-axial discharges built and tested in our laboratory in previous years [9, 10]. The linear-geometry, non-coaxial Hall plasma thruster has been fabricated and operated at near-design conditions. Operating characteristics are presented for both alumina and boron nitride acceleration channels for a range of peak magnetic field strengths.

2. Review of Hall thruster physics

Modern co-axial Hall plasma thrusters that operate in the 1–5 kW power range have been shown to operate with very high thrust efficiencies—around 50%. These thrusters have acceleration channel diameters ranging from 50 to 280 mm. One feature common to these thrusters is that the channel width (W) is approximately 15% of the outer diameter, which itself is about twice the acceleration channel depth (D). In scaling these discharges to operate at various power ranges, it is often desirable to preserve the geometrical relationship between channel width, diameter and depth, although the physical basis for the commonly used geometrical parameters is not well understood.

In a typical Hall thruster, the magnetic field near the channel exit is sufficient to trap the electrons in cyclotron motion. The electron orbit radius (Larmor radius) is generally smaller than the electron mean free path λ and the acceleration channel width W. In this way, the electrons are confined to the magnetized portion of the plasma discharge. The Larmor radius, being dependent on particle mass, is much larger for ions, so they are largely unaffected by the magnetic field. The electron Larmor radius, r_e, scales as:

$$r_e \sim \frac{T_e^{1/2}}{B}. \tag{1}$$

Here B is the magnetic field strength and T_e is the electron temperature. In the design of a low-power (and hence presumably smaller) discharge, a decrease in W requires a corresponding decrease in r_e. The magnetic field strength can be tailored for proper scaling; however, the electron temperature is not easily adjusted, as it is a consequence of a more complex relationship between geometry and operating conditions. The electron temperature is established through a balance between ohmic dissipation, electron–particle collisions (including ionization), and electron–wall collisions. It was decided instead to scale the magnetic field strength as necessary and apply reasonable scaling arguments to preserve the mean electron energy from one design to another. It is seen from (1) that if the electron temperature is to be preserved in the scaling to lower powers, reducing the characteristic size of the thruster requires a concomitant increase in the operating magnetic field strength.

In a Hall discharge's use as a propulsion device, it is desirable to efficiently utilize the propellant, by achieving as high an ionization fraction possible. In scaling a higher power Hall discharge to lower powers, it is therefore desirable to preserve the ratio of the characteristic time to ionize the propellant to the residence time of the propellant in the discharge channel. The ionization time can be found from the inverse of the volumetric rate of ionization R_i, which scales linearly as the electron and neutral densities (n_e and n_a):

$$R_i = n_e n_a \alpha_i(T_e). \tag{2}$$

Here, $\alpha_1(T_e)$ is the temperature-dependent electron impact ionization rate coefficient. The characteristic time for ionization is $\tau_i = n_e/R_i$:

$$\tau_i = 1/n_a\alpha_i. \tag{3}$$

The residence time for a neutral atom can be found by dividing the acceleration channel depth D by the velocity of the neutrals, so it is expected to scale as:

$$\tau_R \sim D/T_a^{1/2}. \tag{4}$$

Here, T_a is the neutral xenon temperature, which is assumed to be relatively uniform, and which will largely control the gas dynamic behaviour of the neutrals within the channel. The ratio of these two parameters, the ionization time over the residence time, scales as

$$\frac{\tau_R}{\tau_i} \sim Dn_a \tag{5}$$

where we assumed that the neutral xenon temperature (along with the electron temperature) is invariant to scale. As we shall see, this assumption regarding the invariance in T_a may be tenuous, since the xenon temperature will depend on the anode and channel wall temperatures, both of which are likely to be considerably higher for a low-power device because of the geometric scaling conclusions arrived at below. A consequence of (5) is that a geometric reduction in the channel depth requires a corresponding increase in the neutral density to preserve the ratio of time scales. As we shall see from the next section, this density increase is achieved by properly scaling the mass flow rate and the channel area.

The axial variation in the magnetic field is also known to have a large impact on discharge performance. In a modern co-axial Hall thruster, the radial magnetic field is sharply peaked near the exit of the acceleration channel, with a distribution width that is much less then the channel depth. A high magnetic field near the anode can lead to a large anode fall loss as electrons experience resistance to current flow. Since magnetic fields are difficult to shape, especially for co-axial designs, the depth of the channel is often dictated more by the magnetic field distribution than geometric scaling of the channel length. An advantage of a linear geometry over a co-axial one is the ease at which a desired magnetic field distribution can be achieved with a less complicated magnetic circuit.

3. Thruster scaling implications

Based on the physics presented in the previous section, the scaling of the discharge is relatively straightforward. We treat the desired discharge voltage ϕ_d as a design parameter, as it directly determines the ion velocity (and hence specific impulse of the thruster), which is often dictated by the satellite mission objectives.

We continue with the assumption that the electron temperature can be preserved with proper scaling. This is justified if we can argue that for a reduction of the total power by some factor ζ, the rates of energy loss and thrust power are correspondingly reduced by the same factor. The reduction in discharge power without a reduction in the discharge voltage implies a reduction in the overall discharge current. However, for proper geometric scaling, the area is correspondingly reduced by the factor ζ^2, so the current densities must be increased by the factor $1/\zeta$. The necessary scaling in the ion current density (and hence thrust power) is achieved if the plasma density is correspondingly increased, since the velocity is unchanged. The necessary scaling in the axial electron current density is achieved if the axial electron drift velocity, V_{ed}, is arguably scale-invariant. As we have discussed previously [8], both the anomalous Bohm transport and wall collisions will give rise to drift velocities that are scale-invariant. The axial drift velocity associated with Bohm transport is determined by the ratio of the electric field strength, E, to the magnetic field strength

$$V_{ed\ Bohm} = \frac{e}{16B}E \sim \frac{E}{B} \tag{6}$$

which will be preserved through a geometric scaling. If the cross-field transport is largely controlled by wall collisions, then, for highly magnetized electrons ($\omega_{ce} = eB/m_e \gg \nu_{wall} = C_e/W$, the wall scattering frequency), the axial electron drift velocity is approximately

$$V_{ed\ Wall} = \frac{eE\nu_{Wall}}{m_e\omega_{ce}^2} \sim EW \tag{7}$$

which will also be preserved with the proper geometric scaling since the magnetic field scales as $B \sim 1/W$, as discussed earlier (here, C_e is the mean thermal electron speed, which is preserved if the temperature is preserved, and e and m_e are the charge and mass of the electron, respectively). The increased electron number density (by the factor $1/\zeta$) is achieved because the corresponding decrease in the mass flow rate results in an increase in n_a, since the area is decreased by the factor ζ^2. This relies on the assumption that the ionization fraction is preserved, which is reasonable if the ratio of time scales presented in (5) is also preserved.

Finally, in order to preserve the electron temperature, we must argue that the electron energy loss rates will also scale in proportion to the decrease in power. It is easily shown that the necessary scaling is obtained if the dominant energy loss mechanism is through wall collisions. It is noteworthy that volumetric ionization will also satisfy the scaling condition, since the energy loss rate through ionization is

$$E_i = n_e n_a \alpha_i V_c \varepsilon \sim \varsigma. \tag{8}$$

Here, V_c is the channel volume and ε_i the ionization energy of xenon.

One undesirable consequence of the geometric scaling for operation at reduced power levels is an increase in heat flux to the channel walls [7]. Since the power is reduced by the scaling factor ζ and the wall area reduced by ζ^2, the heat flux to the walls will increase by a factor of $1/\zeta$. This scaling consequence may prove problematic for very low-power (and consequently reduced size) Hall plasma thrusters.

It is noteworthy that the decreased residence time of the neutral xenon in the channel (see (4)) should result in a shift to high frequencies in the characteristic breathing instability often seen in the 7–10 kHz frequency range in higher power devices [11]. While we predicted this shift in an earlier paper [8], the poor performance of the low-power thruster presented in that study precluded such a measurement. We have characterized the current oscillations in the discharge reported on here, and have found the oscillation frequencies to be consistent with the nearly 1/10 scaling carried out in this study.

In summary, if it is desired to scale the power of a Hall thruster by some arbitrary factor ζ, then the characteristic scale lengths of the thruster and mass flow rates should be scaled by the same factor, ζ. The appropriate adjustment to the magnetic field (preserving its shape) is to increase it by the factor $1/\zeta$. With these scaling laws, according to the arguments presented above, the electron temperature should be preserved, as well as the ratio of electron current to ion current.

4. Linear geometry implications

In a weakly collisional steady-state plasma, where the electron Hall parameter satisfies the condition

$$\omega_{ce}\tau_e \gg 1 \tag{9}$$

the ratio of the cross-field (axial) electron current to the Hall current is

$$\frac{J_{ez}}{J_{eH}} = \frac{1}{\omega_{ce}\tau_e}. \tag{10}$$

Here, τ_e is the time between electron collisions. If we use the classical electron collision time in (9), we would find that for most modern thrusters, the resulting Hall parameter is typically in the range of 100–1000. Note that the current ratio described in (10) is scale invariant in that the scaling laws introduced here would increase the electron cyclotron frequency in proportion to the decrease in the electron collision time. It is precisely this vast inequality between the axial and Hall currents which prompted the use of a co-axial design in early thrusters since, as mentioned above, a co-axial geometry with a closed electron drift allows the electrons to traverse the annulus many times prior to anode capture.

The presence of an anomalous electron transport mechanism, whether fluctuation or possibly wall-scattering induced, reduces the demand placed on the ratio of the Hall to axial electron current. A value of 16 for the 'effective' Hall parameter, as suggested by the anomalous Bohm mobility, still implies an electron drift direction that is predominantly in the direction of the crossed electric and magnetic field. However, we note that the value of 16 for the Bohm coefficient is strictly speculative, as the effective Hall parameters in modern Hall thrusters have not been accurately characterized, and coefficients within a factor of two or three of this value have been obtained for other plasma devices [5]. It is therefore conceivable that the Bohm coefficient can be less than this value. If so, then the necessity for a closed electron drift is removed, and with an adequate aspect ratio (ratio of channel length to channel depth), a linear Hall thruster with an open electron drift may perform equally well in comparison to closed-drift designs. However, even with an effective Hall parameter of unity, the linear design does impose an asymmetry in the electron flow, giving rise to expected asymmetric current densities within the channel that may impact the discharge performance.

5. Experiment

5.1. Test facility

The Stanford high vacuum test facility has been discussed extensively elsewhere [8–10]. It consists of a non-magnetic stainless steel tank approximately 1 m in diameter and 1.5 m in length. The facility is pumped by two 50 cm diffusion pumps, backed by a 425 l s^{-1} mechanical pump. The base pressure of the facility is approximately 10^{-6} Torr as measured by an ionization gauge uncorrected for mass species. Thruster testing at xenon flow rates of 2–5 sccm results in chamber background pressures in the region of 4×10^{-5} Torr. This indicates that the facility has a xenon gas pumping speed of around 2000 l s^{-1}. Propellant flow to the thruster anode and cathode is controlled by two Unit Instruments 1200 series mass flow controllers factory calibrated for xenon. The propellant used in this study was research grade (99.99%) xenon.

5.2. Linear Hall thruster

The design of the linear Hall thruster studied here is based on the scaling of a co-axial reference thruster recently built by our laboratory and operated at a nominal power of 400–700 W [12]. A scaling factor of $\zeta = 0.1$ was used in accordance with the scaling laws presented in the previous sections, although the performance of the magnetic circuit precluded the use of a channel depth that was one-tenth the depth of the reference coaxial discharge. The channel depth deviated from strict scaling laws in order to reduce the magnetic field strength at the anode, and hence the anode fall losses. A comparison of the coaxial thruster used for scaling and the linear thruster is shown in table 1. A schematic of the linear Hall thruster is shown in figure 2.

The magnetic circuit includes four 90 mm long electromagnet windings consisting of a 9.5 mm diameter core of commercially pure iron with 6 layers of 22 gauge

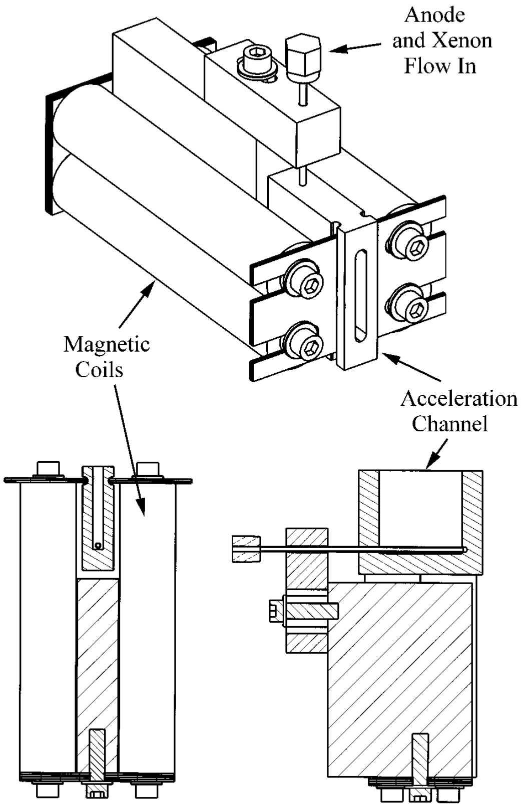

Figure 2. Schematic of the linear-geometry open electron-drift Hall discharge.

Table 1. Comparison of coaxial and linear thruster.

	Coaxial thruster	Linear thruster
Power (W)	500	50
Voltage (V)	200	200
Magnetic field (G)	160	1500
Mass flow rate (sccm) 20	2	
Channel depth (mm)	76	19
Channel length or circumference (mm)	280	25
Channel width (mm)	13	3

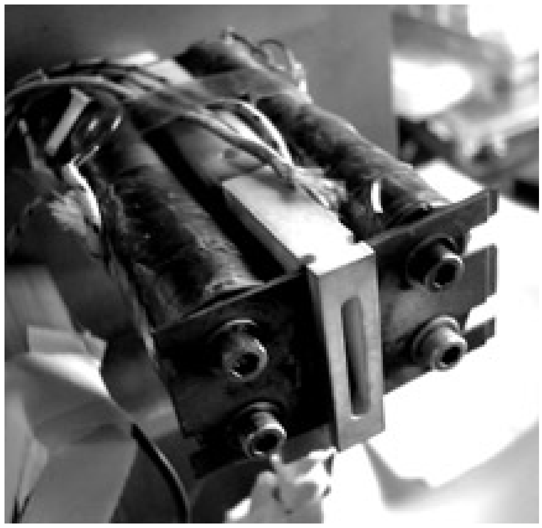

Figure 3. Photograph of the linear-geometry open electron-drift Hall discharge.

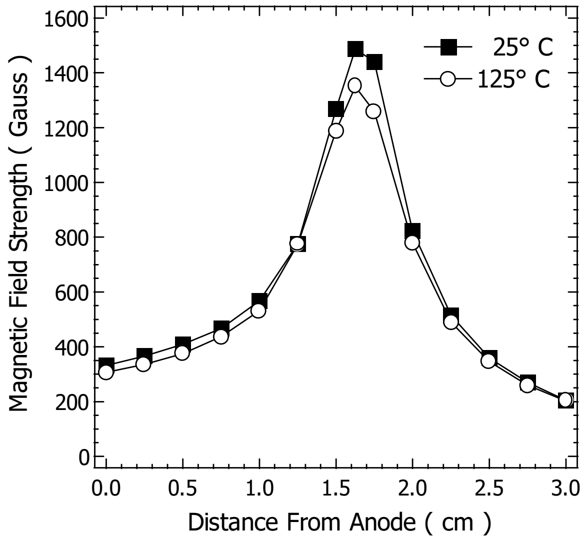

Figure 4. Transverse magnetic field strength variation with axial position. In both cases, the winding current is 1.25 A.

insulated copper magnet wire. The magnetic bottom plate is 3 mm thick silicon steel, whereas the magnetic top plate is 1.5 mm thick silicon steel. The discharge channel was fabricated in two versions, one constructed of high-purity alumina ceramic and the other of boron nitride. The anode is a 1.6 mm diameter stainless steel tube with 14 propellant holes, 0.2 mm in diameter spaced by 1.6 mm. A photograph of the thruster is shown in figure 3.

Measurements of the transverse component of the magnetic field show that the magnetic field near the anode is 23% of the peak value, which is located about 2 mm upstream of the channel exit. The measured field distribution for a winding current of 1.25 A is shown in figure 4 for two different temperatures. These measurements were obtained *ex situ*, by heating the entire thruster unit in an oven at ambient conditions while measuring the magnetic field strength. It can be seen that the peak value of 1500 G at room temperature drops to less then 1400 G with a 100 °C temperature rise. This is significant in that the temperature of the acceleration channel has been measured to be as high as 440 °C by embedded thermocouples during operation in the thruster fabricated out of boron nitride.

The cathode used to neutralize the ion beam and support the necessary electric field is an Ion Tech. Inc. HCN-252 hollow cathode. It is capable of supplying a maximum current of 5 A at xenon flow rates of 0.1 to 0.5 mg s^{-1}. It is mounted in front of the thruster such that the hollow cathode exit is 1 cm above the exit of the channel. The cathode is the exact same unit used in the higher power thrusters, and the flow rate used here is comparable to the flow rate through the thruster itself (2 sccm). We expect that the near exit plane xenon density due to the cathode flow will have a negative effect on the discharge performance. However, because the neutral gas density in this low power discharge is about a factor of 5–10 times that in the higher power prototype, the effect is expected to be no greater here than in the higher power version. No attempt at designing and fabricating an appropriately scaled cathode has been made, although the future development of low-power (< 50 W) Hall thrusters will rely on such a development.

The anode of the discharge is powered by a Sorensen SCR600-1.7 laboratory power supply capable of providing 600 V and 1.7 A. The anode also has a 4 Ω resistor in the power line to serve as ballast during initial start of the discharge. The cathode heating element is powered by a low voltage direct-current (DC) power supply capable of providing the 8.5 A required to heat the cathode for startup and 4.0 A after start. The cathode flow rate of xenon was 2 sccm, a typical value used during operation of our higher power co-axial discharges. The cathode keeper uses a Sorensen SCR300-6 laboratory power supply to provide 250 V for initial cathode start and approximately 10 V and 250 mA during thruster operation. The power required for the magnetic circuit solenoids is provided by a Tektronix PS281 DC power supply operating in current limited mode.

The voltage and current of the thruster were recorded by acquiring data through a National Instruments PCI-5102 data acquisition card plugged into a desktop computer. A voltage divider was used so that the 5 V maximum voltage limit to the card was not exceeded while testing the thruster up to 250 V. The current was monitored by measuring the voltage drop across the 4 Ω ballast resistor.

6. Results and analysis

The thruster described was run at near-design conditions. To start the thruster, a glow discharge was initiated with the magnetic field turned off. With the power supply under current limit control and an upper limit set on the voltage, the magnetic field was increased. The discharge intensity greatly increased and changed colour from dull pink to a bright bluish emission as the magnetic field was increased, which is also typical of coaxial designs. A picture of the thruster running at design conditions is shown in figure 5. The voltage gradually increased until it reached the voltage limit setting. The power supply subsequently switched into voltage control, where most of the data reported was taken.

During operation at magnetic fields above 600 G, it was noted that the discharge was slightly asymmetric, being more intense near the side end of the channel in direction of the $\boldsymbol{E} \times \boldsymbol{B}$ electron drift. It was especially apparent during operation of the alumina thruster that this end wall became extremely hot and glowed intensely. This glow was contrasted to the bulk of the thruster channel, which did not show this intense heating. On one occasion, after a few minutes of running the alumina thruster, the acceleration channel cracked along the edge of the glowing area. This failure was probably due to a high thermal stress caused by extreme temperature gradients in this region of the channel wall. Operation with the boron nitride thruster did not result in such an non-uniform temperature field on the insulating wall. This difference between the boron nitride and alumina insulators is attributed to the difference in the thermal conductivity values of the materials. The boron nitride channel end wall in the direction of the electron drift was instrumented with four embedded J-type thermocouples distributed along its length. During

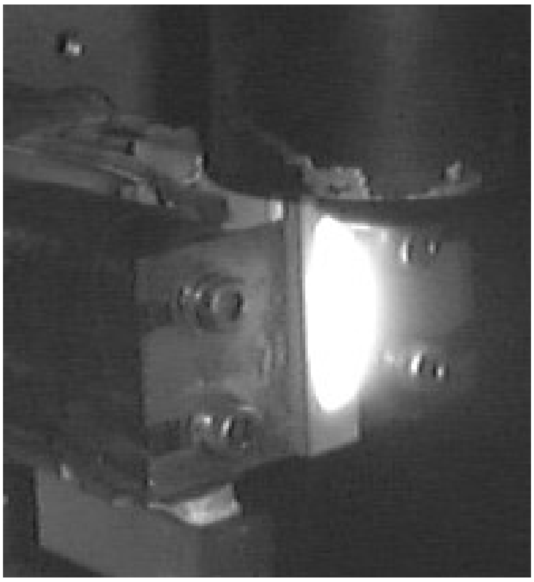

Figure 5. Photograph of the linear-geometry open electron-drift Hall discharge while operating.

nominal operation at 1500 G and 0.7 A, the thermocouples registered temperatures in excess of 400 °C across the entire channel, with the side wall at around 440 °C.

Figure 6 shows the voltage (V)–current (I) characteristics recorded for both the boron nitride and alumina thruster channel for a range of magnetic field strengths and at a xenon flow rate of 2 sccm. The V–I characteristics for the boron nitride channel are somewhat typical of Hall discharges, with an 'ionization branch' at low currents and low magnetic field strengths, and a relatively steep 'current saturation branch' at high operating magnetic field strengths and high discharge current. However, these features are less distinct in the case of the alumina channel. In fact, the V–I characteristics do not show an obvious current saturation regime in this latter case. At relatively low magnetic field strengths, the V–I characteristics of the thruster with the alumina channel wall are nearly indistinguishable from that of the same thruster with a boron nitride wall. This is also the case for all magnetic field strengths investigated, at currents below about 0.5 A. Above these current levels, the V–I characteristics for the alumina channel thruster flatten out (note the apparent 'knee' in the figure), whereas the boron nitride channel thruster voltage rises sharply.

We speculate that secondary electron emission from the alumina channel is partly responsible for the interesting shape of the V–I characteristics. The possible influence of secondary electron emission in establishing the electron transport in Hall thrusters has been discussed in the prior literature [6, 11]. Alumina has a higher secondary electron emission coefficient than boron nitride [13] and, in addition, we expect that the secondary electron emission is sensitive to wall temperature. It was apparent that during thruster operation with the alumina walls, the wall temperature may have been sufficiently high to significantly enhance secondary electron emission. The higher secondary electron emission for the case of the alumina insulator wall would aid electron transport across the magnetic field. As a result,

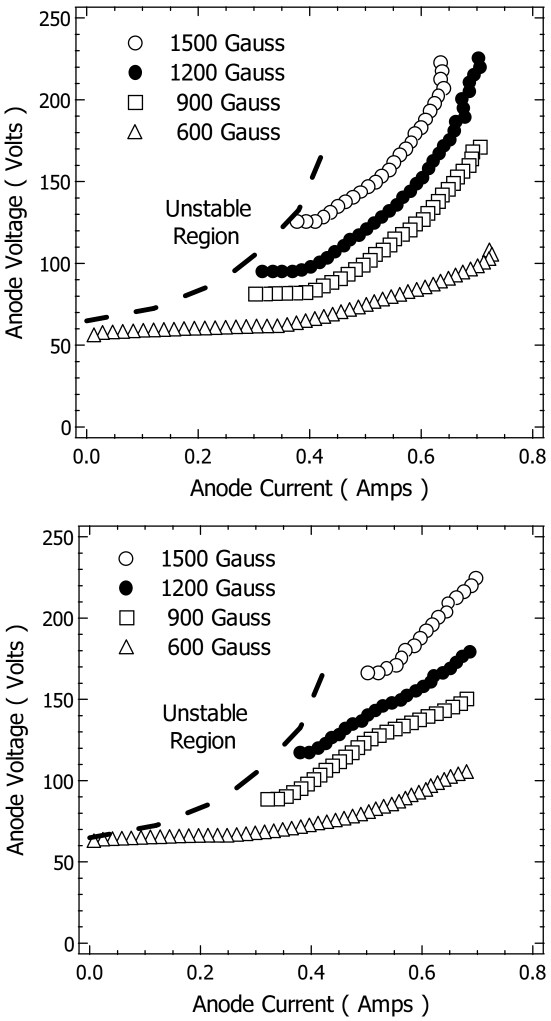

Figure 6. Discharge voltage-current characteristics of the linear-geometry Hall discharge (top) boron nitride channel, (bottom) alumina channel.

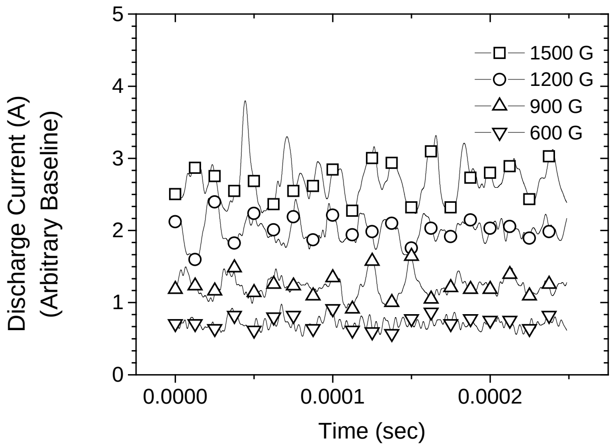

Figure 7. Time-variation in discharge current for the alumina-walled plasma source at a range of peak magnetic field conditions.

the thruster could not support as high a voltage as that supported by the thruster with the boron nitride wall. This conjecture would imply that there is a high electron flux (current) along the side wall opposite the direction of the electron Hall current, an argument that is consistent with the observation that the side wall of the boron nitride thruster is found to experience significant erosion. In a recent study by Raitses *et al* [6], it was noted that there were significant differences in the $V-I$ characteristics of a thruster operating with a machinable glass channel and a boron nitride channel. In that study, enhanced axial transport in the thruster with the machinable glass channel was attributed to wall effects, decreasing the thruster efficiency at high operating voltages. The qualitative findings reported on in this study agree with these past observations. It is also noteworthy that the conjecture that there is an enhanced electron current due to wall collisions is supported by the relatively poor efficiency of this discharge, as an upper limit of the ratio of the ion current to electron current is no more than 30%, based on full utilization (ionization) of the propellant.

In all cases, the thrusters exhibited a region of unstable operation. At all magnetic field strengths except the lowest value shown, the discharge had a low current limit in its operating envelope. Attempts to operate or start the discharge in this region would fail. We speculate that this region of instability is closely tied to the requirement for enhanced electron transport and that, at low currents and high magnetic fields, the anomalous transport process cannot provide the necessary current to maintain the discharge.

The fact that the thruster ran without a mechanism for closing the Hall current confirms the importance of an electron transport process that is due to plasma fluctuations and/or wall effects associated with secondary electron emission. As in the higher power co-axial discharges, the linear discharge studied here also exhibited plasma fluctuations, which were detected as fluctuations in the external circuit discharge current.

Figure 7 shows the oscillations in the discharge current of the linear thruster operating with the alumina channel wall for a range of peak magnetic field strengths and at a discharge current of 0.7 A. The fluctuations in the discharge current for the boron nitride wall were qualitatively similar. It is apparent that at low magnetic fields, there is a relatively low frequency oscillation, on which higher frequencies are superimposed. The low frequency oscillation increases in amplitude and in frequency as the magnetic field is increased. These intense low frequencies observed in this linear device are similar to those seen in co-axial devices, and are believed to be the so-called ‘breathing’ mode of oscillation associated with the neutral xenon transit through the ionization zone [14]. This instability is associated with the disturbance in the balance established between the depletion of neutrals in the channel as a result of ionization, and their replenishment. Since the length of the ionization zone in this low-power Hall discharge is scaled to be some 5–10 times shorter than that of our reference thruster, the frequencies of these disturbances are expected to be at least a factor of five higher than those seen in our higher power co-axial devices.

Figure 8 compares the Fourier analysis of the temporal fluctuations in discharge current of the reference 400 W (200 V, 20 sccm, 160 G, 2 A) co-axial thruster and the low-power linear thruster operating with the alumina channel

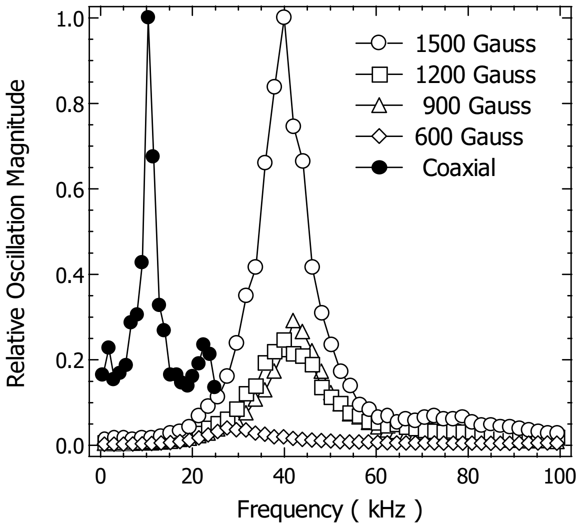

Figure 8. Low-frequency spectral analysis of the temporal fluctuations in the discharge current. Included in the figure is the spectral distribution of the fluctuations seen in the higher power co-axial discharge for comparison.

wall (data shown in figure 7). It is apparent that the low-power thruster has a strong low-frequency mode, similar to that seen in the co-axial high-power devices, at frequencies that are approximately a factor of four times that of the higher power thruster. As the magnetic field is increased the frequency of the fluctuations in the anode current also increase, until a magnetic field strength of 900 G, beyond which it remains constant. This result is seemingly inconsistent with the theoretical predictions of Boeuf and Garrigues [14]. However, a direct comparison to the results in [14] is difficult to make, since in our studies, the current is held constant while the magnetic field is increased (resulting in increased discharge voltages). In the calculations of Boeuf and Garrigues, the voltage was varied at constant magnetic field (giving rise to varying current) and/or the magnetic field was varied at constant voltage. As discussed in [14], the frequency of this mode is seen to increase dramatically with voltage (at constant magnetic field). The response that we see is therefore likely to be a result of the response in the frequency to changes in both the voltage and the magnetic field.

It is interesting to note that at the highest magnetic field studied, there is a superimposed high-frequency oscillation at about 80 kHz. Through particle simulations, Boeuf and Garrigues [14] also discovered the presence of strong disturbances in the plasma density and electric field upstream near the anode when the magnetic field continues to persist near the anode. The weak intensities seen here at the highest magnetic field studied may be a consequence of these near-anode instabilities, although a precise characterization of these instabilities in a linear geometry must still be performed. In a related study, we have identified the presence of near-anode instabilities in this frequency range (40–100 kHz) in co-axial Hall discharges [15].

7. Summary

An analysis and arguments for the scaling of a Hall plasma thruster to low powers was presented. A linear-geometry version of a thruster operating in the 50–100 W power range has been fabricated and operated at near-design conditions. Preliminary results obtained so far indicate that at the scaled power levels, these low power plasma discharges operate at much higher channel wall temperatures. This increased heat flux may be a major impediment to the extended operation of very low power devices.

The linear Hall plasma thruster reported on here is found to have the characteristic discharge instabilities seen in higher power co-axial versions. Although we have not performed an extensive analysis of the thruster performance, it does appear that the linear device behaves in many ways similarly to those of a co-axial design with a closed electron drift. Since the linear discharge operates without a closed Hall current, it suggests that there must be an anomalous mechanism for cross-field electron transport.

This device might prove most useful for investigating various materials for use as acceleration channels in Hall thrusters. The linear-geometry design allows easy fabrication from a variety of materials. A study of the operating characteristics of thrusters constructed with insulating walls fabricated from a wide variety of materials would be useful for understanding the effect of secondary electron emission on electron transport.

Acknowledgments

This work was supported by the Air Force Office of Scientific Research, with Dr Mitat Birkan as the contract monitor.

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