The Impact of Magnetic Field Coupling Between Channels in a Nested Hall Thruster

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The coupling between the channel magnetic fields in the X3, a three-channel, 100-kW class nested Hall thruster, is investigated numerically and experimentally. Because the nested channels share magnetic core material, it is found that the magnetic fields from the channels can influence one another. Simulation results indicate that the magnetic field of the interior channels can be skewed by the presence of an exterior channel's magnetic field. However, the exterior channel's magnetic field is not skewed when the interior channels' magnetic fields are energized. In order to correct for these effects, it is shown that the coil currents must be tailored between single channel and multi-channel operation in such a way that will maintain the classic "lens" shape of modern Hall thrusters. Experimental measurements of the X3 thruster were performed to check the efficacy of the disparate magnetic field configurations. It is shown that if the cross-coupling in magnetic fields between channels is not successfully corrected for, the thrust suffers 3.4%. This is turn causes the efficiency and specific impulse to also degrade for the given operating condition. Additionally, when running the inner and middle channel together, the inner channel oscillations increase by 11% if the uncorrected, single-channel magnetic field settings are used. In light of these findings, recommendations for how to correct for magnetic field aberrations in nested Hall thrusters are discussed.

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Nomenclature

$()_{IC}$ = inner channel
$()_{MC}$ = middle channel
$()_{OC}$ = outer channel
g = gravitational constant
I_{P2P} = peak-to-peak AC current oscillations
I_{DC} = DC discharge current
I_{sp} = specific impulse
$\dot{m}$ = mass flow rate
P = power
R = ratio of inner coil current to outer coil current
T = thrust
η = efficiency

I. Introduction

Studies have shown that high power electric propulsion systems (> 100 kW) are well-suited for deep space applications including human missions to Mars.[1–4] While there are many methods for achieving electric propulsion systems at this high power scale, one particularly attractive and relatively new concept is the so-called Nested Hall Thruster (NHT).[5,6] This concept relies on concentrically nesting multiple annular Hall discharges together. This achieves, at high power, many of the advantages of single channel Hall thrusters such as high efficiency and high thrust-to-power but with a lower effective specific mass and substantially expanded throttling range. In light of the potential advantages offered by NHTs, the University of Michigan, in conjunction with NASA Glenn Research Center, the Jet Propulsion Laboratory, and the Air Force Research Laboratory, has invested in development programs to explore the feasibility and efficacy of NHTs. The first thruster to emerge from these efforts was the X2, a proof-of-concept two channel, 10-kW class, nested Hall thruster tested primarily at the University of Michigan.[5] Following the successful demonstration of this system, the lessons learned were applied toward constructing the X3,[6] a three channel nested Hall thruster with a designed operational power of 200 kW. This thruster is currently baselined for the NextSTEP program partnership led by Aerojet Rocketdyne.[7–9]

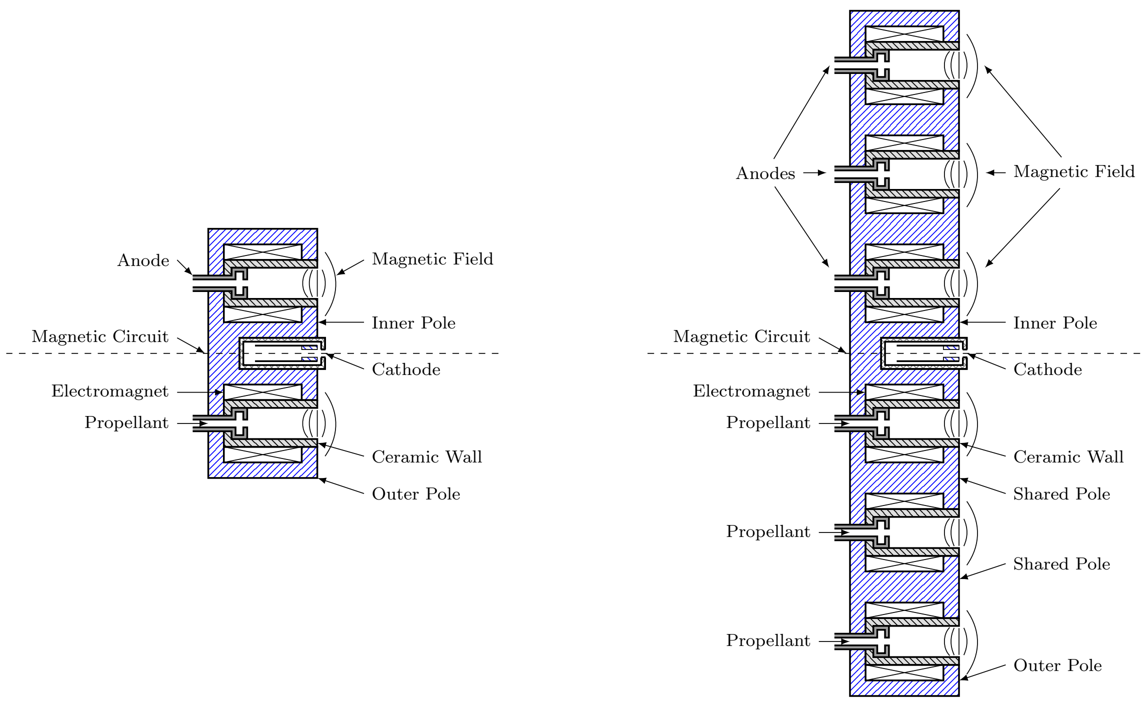


Figure 1: The magnetic configuration of a single channel Hall thruster (left) and a nested Hall thruster (right) . The dashed line is an axis of symmetry. These figures are notional.

While nested Hall thrusters have significant enabling characteristics for high-power operation, they are still a relatively nascent technology with many unanswered fundamental questions about their operation. These largely center around how the multiple channels in these devices couple and interact. Previous studies,[10,11] for example, have explored how neutral gas originating from the adjacent channels affects the performance of nested Hall thrusters. These investigations showed that the increased neutral pressure near the thruster led to increased neutral ingestion and movement of the acceleration region axially inwards. In this same vein, there is an open question about how the magnetic fields for each channel may interact with one another. Indeed, nested Hall thruster magnetic circuits inherently are more complicated than their single channel counterparts. Each channel of the nested Hall thruster shares some of its magnetic circuit components with the other channels of the thruster (Fig. 1). This makes producing the desired magnetic field much more complicated than for a single channel and raises the possibility that the magnetic field of one channel will have a significant impact on another channel. To date, although NHTs have been successfully built and tested, it still is unclear if and how this cross-talk between magnetic fields in the channels might impact overall thruster performance. The goal of this work is to explore this question with the specific aims of determining the influence of the channel interactions on magnetic field topology and performance.

As such, the paper is organized in the following way: magnetic field simulations of each individual channel are presented, then the combination of single channel setting in each multi-channel configuration is presentation, and subsequently, the balanced field for each multi-channel configuration is presented. Comparisons between the single channel optimized field and multi-channel optimized field settings are made. Finally, in order to explore the implications of the cross-coupling, we present performance data of the thruster in a nested configuration taken at both single channel and balanced multi-channel magnetic fields. We conclude with a discussion of the recommendations for adjusting magnetic fields in nested Hall thrusters.

II. Methods

A. Magnetic Field Design Goals

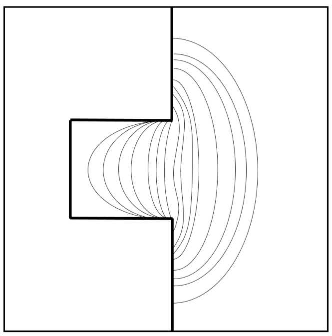
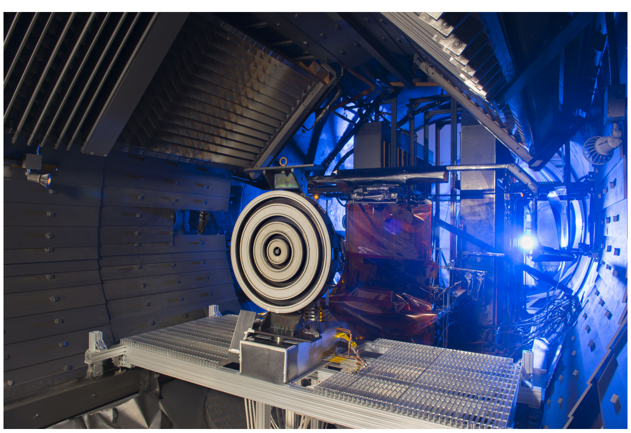


Figure 2: Illustration of a plasma magnetic lens.

Before discussing in detail the adverse effects of cross-field coupling between the channels in NHTs, we briefly outline here the criteria we employ for determining whether or not the magnetic field topography in a given channel is "correct" or "skewed." To this end, we note that previous studies on the magnetic field configuration in Hall thrusters have shown that the optimal shape for maximizing efficiency is the "plasma lens".[12,13] This configuration generally refers to a shape where the field curvature focuses the ions onto channel centerline far downstream.[14] The study[14] also showed that magnetic field symmetry within the channel is critical to high thruster performance. An example of the curvature can be seen in Fig. 2 where we have drawn notional field lines to illustrate the geometry. This canonical shape is the benchmark shape we used for our investigation to evaluate whether or not each channel's topography was balanced or not.

B. Thruster



(a)

(b)

Figure 3: (a) the X3 nested Hall thruster installed in VF-5 at NASA's Glenn Research Center and (b) firing in three channel configuration during testing at NASA Glenn.

The X3 (Fig. 3) was the NHT we examined in this study. It is a three-channel system featuring discharge channels with similar cross sections, magnetic fields and gas distributors.[6,15,16] The thruster is approximately 80 cm in diameter and weighs 230 kg. It employs a centrally mounted lanthanum hexaboride cathode with external flow to reduce energetic ion production.[17] Each channel has two dedicated electromagnetic coils to generate the magnetic field. However, in order to reduce overall mass of the thruster, magnetic cores are shared between channels. For instance, as seen in Fig. 1, the outer core for the inner channel is also the inner core for the middle channel. The magnetic fields on the inner and outer channel consequently point in the opposite radial direction as the middle channel. This shared core configuration inherently leads to the possibility of interactions between the channels when multiple are operating.

C. Simulation

In order to generate maps of the X3's magnetic field, we created a model in the commercial program, Infolytica's MagNet v7.7. We employed the solver criteria and convergence settings recommended from the optimization study performed by Conversano.[18] Since the X3 geometry is constrained by the model, the input variables into the program for generating the magnetic field lines are the currents to the electromagnetic coils. To this end, for a given channel, we define the coil current ratio, R, as the ratio of the inner to the outer coil current for a given channel. Since each channel has a pair of coils, each channel can have a unique coil current ratio. From this point forward, the ratio of currents from our results will be called R_{IC}, R_{MC}, and R_{OC} for the inner, middle and outer channels respectively.

D. Experimental

In order to quantify the effect of changing the magnetic field shape on thruster performance and stability, we also included an experimental campaign for this investigation. This testing was performed in Vacuum Facility 5 (VF5) at NASA Glenn Research Center. VF5 is a 4.6 m diameter, 18.3 m long cylindrical vacuum chamber that features 33 m^2 of cryogenic pump surfaces. The facility walls and cryogenic panels are lined with graphite plates to minimize backsputter during thruster operation. Pressure inside the facility was monitored using four Stabil Ion Gauges mounted in various locations. The pressures cited in this study stems from the gauge mounted in the exit plane of the thruster approximately 1.5 meters from thruster centerline, pointed downstream. This gauge was calibrated on xenon. Further description of the setup can be found in the companion paper.[7]

During operation in VF-5, each channel of the X3 was run from a separate commercially available power supply. The electrical common for all discharge channels was shared through the single lanthanum hexaboride centrally-mounted cathode.[7] Power to the six electromagnets and the cathode was supplied using commercially-available rack-mounted power supplies. High-purity xenon propellant was provided to the thruster through five commercially available mass flow controllers plumbed to stainless steel line.

We employed a thrust stand to measure thrust and subsequently to calculate efficiency and specific impulse. The thrust stand we used was an inverted-pendulum design based largely on the X3-dedicated thrust stand previously developed at the University of Michigan.[19] The full range of the thrust stand is 8 N of thrust. The thrust stand operated in null mode, was calibrated in-situ using a string of known masses, had active inclination control, and was water-cooled to protect against thermal drift during thruster operation, following industry best practices.[20–22] We performed in-situ calibrations of the stand at the beginning and end of each test day, and additionally took zeros periodically throughout the day. The thrust stand was found to have a statistical uncertainty of approximately 2%. Further description of the thrust stand is provided by Hall.[7]

III. Results and Discussion

A. Simulation

We present in this section a number of different studies for the magnetic field interactions in the studies. These include characterizations of the magnetic field when only a single channel is energized as well as when multiple channels are energized. To this end, we begin with the results from single channel characterization. Fig. 4 shows cases where only one channel was energized at a time. In each case, we have crafted the coil ratios (R) to achieve the magnetic topography shape identified in Sec. IIA. The ratios, R, corresponding to the balanced single channel settings are 1.58, 1.36 and 0.98 for the inner, middle and outer channels respectively.

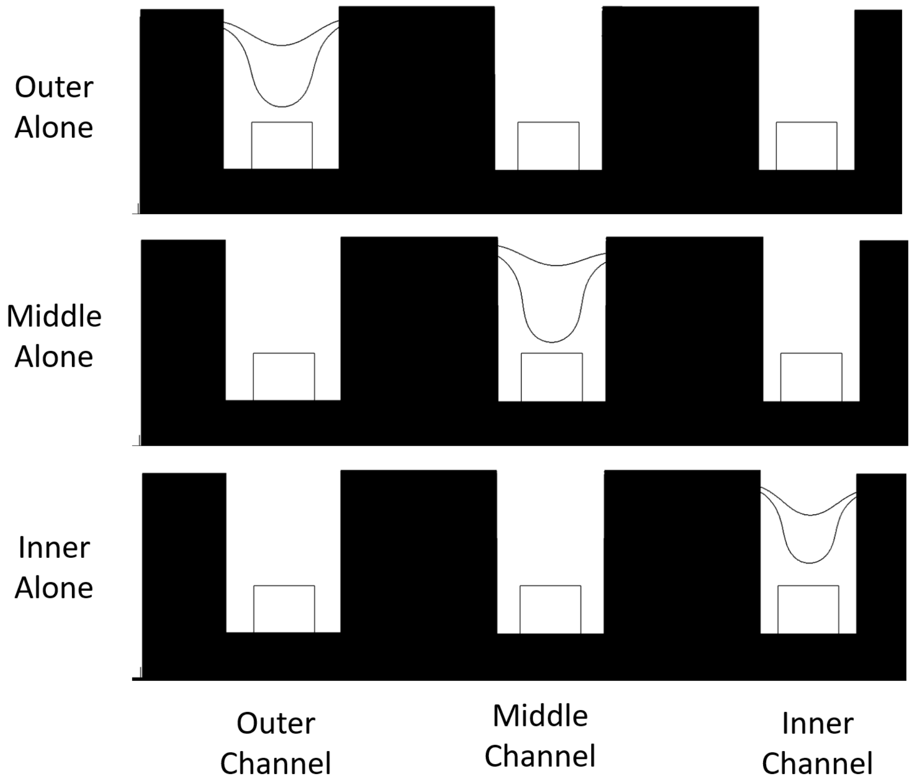


Figure 4: The plasma lens topography for the inner, middle and outer channels operating alone. In each graph, only the energized channel magnetic field is shown for clarity.

For the next case study, we kept the coil settings found from each channel being energized alone for the inner and middle and then energized both coils at the same time. The results are shown in Fig. 5 (top) where we can see that although the middle channel remains unperturbed, the inner channel topographic lens has been significantly skewed toward in outer wall of the discharge chamber. This result is likely the consequence of the fact that the channels share a magnetic core. It is interesting to note that the inner channel is affected drastically while the middle channel field was not affected much. Ultimately, however, this is the first marked evidence that field interaction is a real possibility and indeed suggests that it is not possible to simply assume that balanced single channel configuration will work when both are energized.

In order to correct for this error, we systematically changed the coil ratios until we arrived at R_{IC}=0.79 and R_{MC}=1.38. This is a 50% reduction in the ratio for the inner channel. The result is shown in Fig. 5 (bottom) where the magnetic lens topography has been recovered. Thus, although there is evidence that the magnetic fields in the channel are changed by the adjacent channels, it is critical to note that re-balancing of the field to achieve the plasma lens is possible. It follows then that each operating condition must be optimized individually (single channel, multi channel, etc.).

One possible exception to this rule is the case of the inner and outer channels together. These channels have very few shared magnetics. Indeed, their only connection is through the back pole. Therefore, the expectation was that there would be little interaction. However, as seen in Fig. 6 (top), this is not the case.

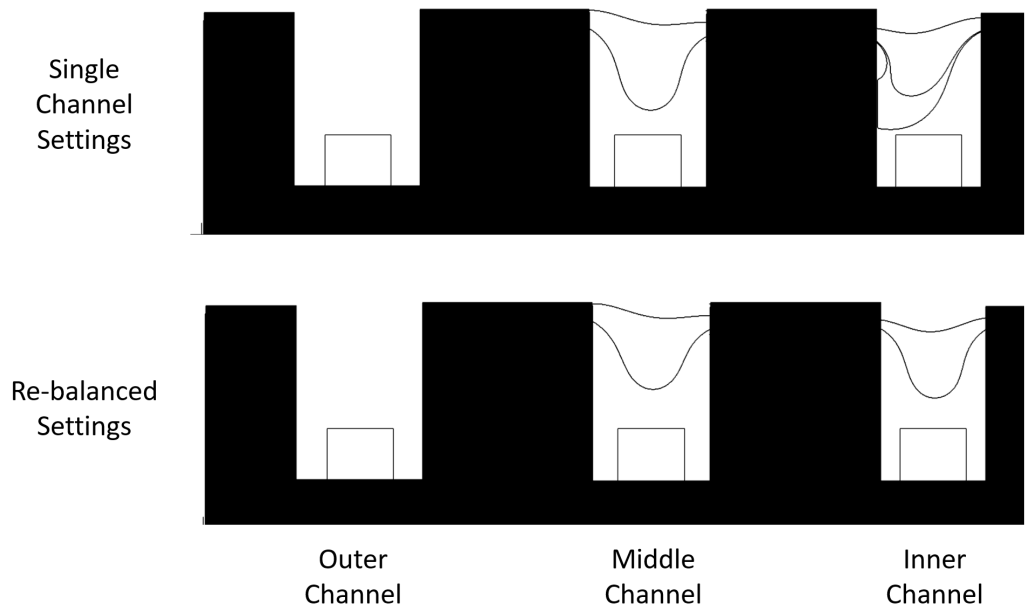


Figure 5: Results for the inner and middle channel configuration using the single-channel ratios (top) and corrected ratios (bottom). The outer channel field lines are not shown.

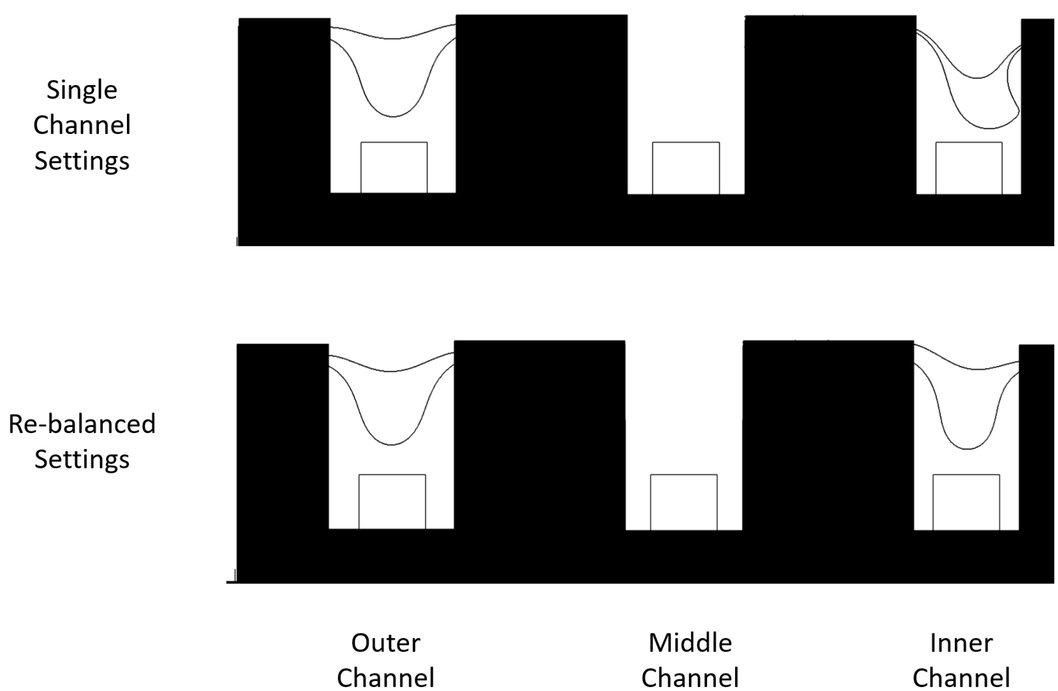


Figure 6: Results for the inner and outer channel configuration using the single-channel ratios (top) and re-balanced settings(bottom). The middle channel (center) does not have its magnetic field energized. Interestingly, even though there are few shared magnetics, the inner channel field is skewed by the presence of the outer channel field. The middle channel field lines are not shown.

Again, the inner channel is affected while the outer is not. The ratios to re-balance this field were 2.43 and 0.98 for the inner and outer channel respectively. Interestingly, when the middle channel is energized, the inner channel skews radially outward, but when the middle channel is not energized, the inner channel skews radially inwards. A pattern has also begun to emerge where the radially inward channels are affected by the outermost energized channel but not vice versa. Seen in Fig. 7 is the three channel results using both the single channel ratios and the re-balanced ratios. The fields were rebalanced using current ratios of 1.21, 0.86, and 1.13 for the inner, middle and outer channels respectively. Indeed, as seen in Fig. 7 (top), the middle and inner channel are affected in three-channel operation while the outer is not. Therefore, we remark here that in this nested Hall thruster configuration, it appears as if any channel located radially inward will have a topography change due to a radially outward channel energizing its magnetic field, but not vice versa. Indeed, we found this held true for all four nested channel configurations for the X3.

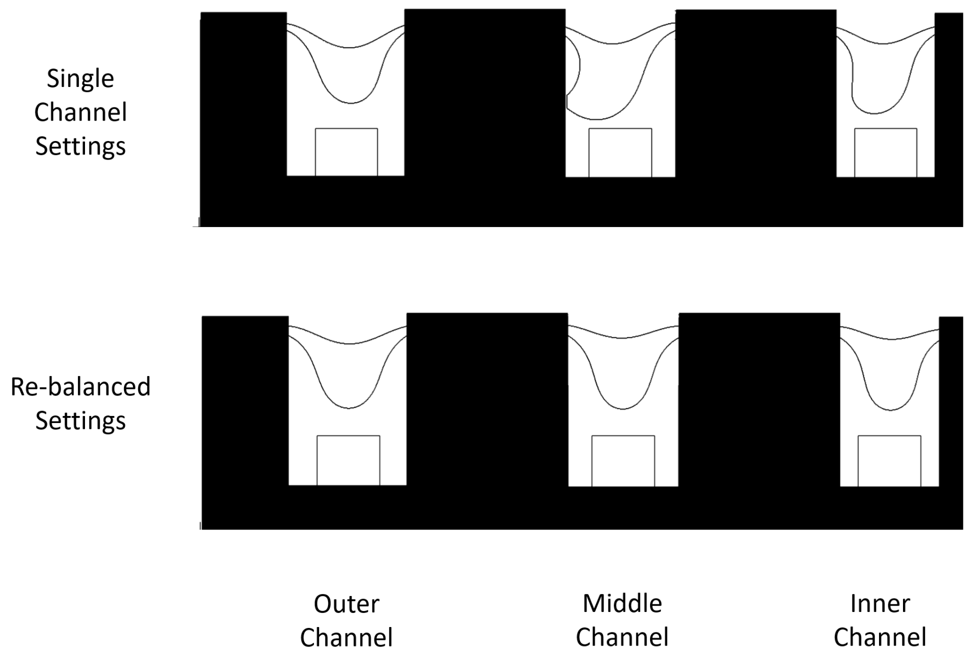


Figure 7: Results for the inner, middle, and outer channel configuration using the single-channel ratios (top) and re-balanced settings (bottom). Results from the single channel settings show that the inner and middle channels are skewed while the outer channel is not by the presence of the other magnetic fields.

B. Experimental

While the previous section showed that it is necessary to take into consideration the other channels when operating in multi-channel mode in order to achieve the lens topography, it is not necessarily evident that the changed magnetic field topography is a cause for concern. Indeed, the most dominant changes in topography appear to occur closer to the anode where the magnetic field is relatively weak, therefore having a minimal impact on the acceleration processes in the thruster. In other words, it is possible that this re-balancing has a minimal impact on overall performance. However, there are likely other insidious effects on the thruster such as heat load and lifetime degradation. In order to explore this possibility, we conducted an experimental campaign to quantify the consequences of not correcting for the cross-channel magnetic coupling.

Specifically, we compared the case of two channel operation (inner and middle) where we used the settings for the single channel configurations (Fig. 4 top) and the correctly rebalanced (Fig. 4 bottom). Detailed here are the results from this experimental testing and their relation to the simulations. The total number of test conditions are compiled in Table 1.

Table 1: Test Matrix

Test Point	IC Voltage [V]	IC Current [A]	MC Voltage [V]	MC Current [A]	Magnetic Field
1	300	27	0	0	$R_{IC} = 1.58$
2	0	0	300	64	$R_{MC} = 1.36$
3	300	27	300	64	$R_{IC} = 1.58$ $R_{MC} = 1.36$
4	300	16.4	300	39.6	Optimized Settings

The background pressure during testing was 6.6×10^{-6} Torr-Xe during test point 1, 1.5×10^{-5} Torr-Xe during test point 2, and 2.0×10^{-5} Torr-Xe during test points 3 and 4. The thrust numbers here are not corrected for neutral ingestion. Thrust stand measurements were used to calculate specific impulse as,

$$I_{sp} = \frac{T}{\dot{m}g} \tag{1}$$

where T is the thrust, $\dot{m}$ is the mass flow rate, and g is the gravitational constant. The thruster efficiency is calculated as,

$$\eta = \frac{T^2}{2\dot{m}P} \tag{2}$$

where P is the total power of the thruster (discharge and magnets). The results from the test can be seen in Table 2. Also shown are the peak-to-peak plasma oscillations with respect to the mean discharge current for each channel during the tests.

Table 2: Performance Results from the X3 testing

Test Point	Discharge Power [kW]	Thrust [mN]	I_{sp} [s]	Efficiency	$\left(\frac{I_{P2P}}{I_{DC}}\right)_{IC}$	$\left(\frac{I_{P2P}}{I_{DC}}\right)_{MC}$	Magnetic Field
1 (Inner)	8.2	570 ± 24	1960±81	0.67 ± 0.06	0.34	-	R_{IC}=1.58
2 (Middle)	18.7	1280 ± 36	1930±54	0.65 ± 0.04	-	0.20	R_{MC}=1.36
3 (Dual)	26.9	1780 ± 44	1900±47	0.62 ± 0.03	0.59	0.26	R_{IC}=1.58 R_{MC}=1.36
4 (Dual)	27.0	1840 ± 45	1950±48	0.64 ± 0.03	0.48	0.26	R_{IC}=0.79 R_{MC}=1.38

As is predicted by the simulations, the results indicate that the thruster performance is lower when using single channel magnetic field for multi-channel operation as compared to single channel operation. When using the optimized fields, the thruster performs on par with the single channel results. Going to the optimized fields yields about a 3.4% increase in thrust. The efficiency and specific impulse also increase for dual channel mode. This result confirms that the skewing of the magnetic field seen in Fig. 5 negatively impacts the performance of the device. Interestingly, it also appears as if moving to the re-balanced configuration results in the discharge oscillations also decreasing. This result can be linked to observations by Hofer et al[23] who showed that achieving the plasma lens decreased the oscillation strength. Conversely, the results here show that when using the single-channel coil ratios, the inner channel oscillation magnitude is significantly higher than the balanced field while the middle channel does not change much. This is expected as the simulations showed that using the single-channel coil ratios only strongly affected the inner channel field. Since the middle channel field using single-channel coil ratios was largely unaffected, it is no surprise that the oscillations largely do not change.

C. Discussion

The ultimate finding from the above results is that magnetic coupling between channels can adversely impact the lensing and therefore performance of each channel. The operator therefore must take care to correctly study and optimize the magnetic field lines and coil current ratios when operating these devices. With this in mind, the above results suggest some notable trends and guidelines for how to implement these adjustments:

- The inner channel ratio must be adjusted down if the middle channel is energized, otherwise it must be adjusted up.
- Besides minor adjustment in the inner-middle firing configuration, the middle channel ratio must always decrease. However, the amount the ratio must be adjusted differs different depending on the operating condition. This is plausibly explained by the fact that the magnetic materials being shared are slightly different in every configuration.
- In the case of three channel operation the inner channel must be changed differently than the inner and middle operation due to the outer channel affecting both the middle and inner channels.

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In addition to these considerations, we note here as well that although 3% changes in performance are notable, they are not extreme, and in some cases, are not even extending beyond the uncertainty of the measurement. However, we note that this proof of concept in this study was only for one channel configuration at one discharge voltage. It is indeed possible that the adverse consequences of uncorrected magnetic field cross-channel coupling will be be greater at other operating configurations. Moreover, other studies[23] have shown that skewing has a larger impact at higher discharge voltages. As 300 V is the minimum nominal voltage for the thruster, the impact of the skewness, and subsequent return to symmetry, is likely to increase with increasing voltage. As a final consideration, and one that we could not examine here, we note that the loss of lensing, or the skewness, likely has a large impact on thruster lifetime. Skewing the field into the walls will likely allow for enhanced plasma flux into the walls. This, in turn, may drastically increase channel erosion. In order to avoid this, proper plasma lens-ing must occur.

IV. Conclusion

We have studied the phenomena of magnetic field coupling between channels in a nested Hall thruster configuration. Using the 200-kW X3 thruster as our case study, we have showed that when multiple channels are active, they can influence and skew the magnetic topography in the other channels. In particular, if a single channel is energized and optimized to yield the ideal “plasma lens”, energizing a channel at a larger radius will radially skew skewed the field lines of the inward channel. This skewing can be corrected by a careful adjustment of the coil current ratios in each channel. Notably, we have found that the outer-most channel is unaffected when the interior channels are energized.

In order to complement our simulation results which showed unambiguously that magnetic coupling between channels is a problem, we also performed experimental measurements to quantify the performance impact of not correcting for the magnetic field skewing. Performance testings shows that the loss of lensing of the magnetic field negatively impacts the performance of the device by decreasing thrust, efficiency and specific impulse while increasing oscillation strength. These findings ultimately indicate that each operating condition for a nested Hall thruster must have its magnetic field shape balanced individually and it cannot be assumed to be the summation of multiple single-channel fields. The guidelines we have offered for performing this re-balancing have already been incorporated into a recent experimental campaign with the X3.[7]

Acknowledgments

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