Experimental and theoretical studies of Hall discharge plasmas have been carried out. The research is categorized as having components related to: (a) fundamental studies of transport in Hall thrusters; (b) development of new diagnostics for probing the near-field, in wall-less acceleration regions; (c) the development of wall-less Hall thrusters, where acceleration and ionization takes place downstream of the channel; (d) two-dimensional (2D) hybrid particle-fluid simulations in the r-z dimensions that capture the evolution of the wall due to erosion over thruster operating life; and (e) the use of this understanding to scale Hall thruster to ultra-low power levels.
1. Executive Summary

The primary objective of our existing grant, as stated in our original proposal, was to (i) develop a better understanding of the electron transport in Hall thrusters; (ii) greatly reduce or eliminate the influence of the walls on the electron transport; and (iii) replace the role of the wall in electron conduction with enhancement and control of the bulk conductivity. In this way, the selection of wall material and thruster geometry can be made independently of its effect that the wall will have on conductivity, so as to optimize the thruster performance with respect to reliability and service life.

2. Technical Summary

2.1 Background

The primary objective of our existing grant, as stated in our original proposal, was to (i) develop a better understanding of the electron transport in Hall thrusters; (ii) greatly reduce or eliminate the influence of the walls on the electron transport; and (iii) replace the role of the wall in electron conduction with enhancement and control of the bulk conductivity. In this way, the selection of wall material and thruster geometry can be made independently of its effect that the wall will have on conductivity, so as to optimize the thruster performance with respect to reliability and service life.

As described below, we have carried out experimental and theoretical studies of Hall discharge plasmas. The research is categorized as having components related to: (a) fundamental studies of transport in Hall thrusters; (b) development of new diagnostics for probing the near-field, in wall-less acceleration regions; (c) the development of wall-less Hall thrusters, where acceleration and ionization takes place downstream of the channel; (d) two-dimensional (2D) hybrid particle-fluid simulations in the r-z dimensions that capture the evolution of the wall due to erosion over thruster operating life; and (e) the use of this understanding to scale Hall thruster to ultra-low power levels.

2.1.1 Transport Studies

Understanding electron transport in Hall thrusters continues to be an overarching problem in Hall thruster physics. In previous years, we have mapped out the axial variation in the Hall parameter in our laboratory Hall discharge. The Hall parameter is a measure of the cross-field electron migration. These previous measurements relied on a compilation of laser and intrusive probe-based measurements of axial electron current density, electric field, and static magnetic field [7]. These measurements can also provide the azimuthal current density distribution. During the past two years, we have further validation of the measured Hall parameter through non-intrusive measurements of the Hall current distribution [17-19]. In addition, we have carried out fundamental theoretical studies of electron transport [10], the goal of which is to derive a transportable expression for electron mobility without having to resort to the use of ad-hoc Bohm or wall collision expressions, which have little physical basis.

Hall Current Diagnostics

During this performance period, we have developed and successfully implemented a novel non-intrusive measurement of the axial variation in the azimuthal current distribution [17-19]. We have employed fast current interruption to generate a signal across an antenna array positioned strategically outside the Al2O3 wall of the discharge
channel. The distributed signals in the six antennas are deconvolved to determine the distribution of the azimuthal drift current at the moment of discharge current interruption. Figure 2 is an illustrative result depicting the measured current density contours for our laboratory thruster operating at 200V. Also shown in the figure is the magnetic field (gray scale map). We have found that the determined Hall current induces a non-negligible field, which results in a shift of the peak in the resultant field towards the anode, and a reduction in magnitude of 5-15%. The axial variation in the vacuum and plasma field are shown in Fig. 3. Also shown in the figure is the measured electric field (from previous data) the peak of which coincides with the determined plasma B-field from these non-intrusive measurements. Finally, Fig. 3 compares the prior intrusive measurements of azimuthal current to the non-intrusive antenna-based measurements. The agreement is very good, providing confidence in both measurements. The discrepancy is attributed to uncertainty in the previous measurements associated with plasma density, which were not expected to be accurate to better than a factor of two because of its intrusive nature.

An archival paper describing these important studies has been completed and submitted for publication [5].

Electron Transport Theory

The Hall-effect thruster exhibits anomalous electron transport - a phenomenon common in magnetized plasma, often attributed to non-steady and/or nonlinear processes. As a result, its electron mobility is not predicted by classical theory, and the magnetic field in the Hall thruster is difficult to optimize. There are two theories that attempt an explanation for anomalous transport: near-wall transport, and fluctuation-induced transport. In all likelihood, both phenomena impact the Hall thruster, but our results indicate near-wall transport is unlikely to be responsible for the electron mobility at low discharge voltage [20]. For this reason, we have studied the impact of fluctuations at low voltage, where wall-effects should not impact our observations.
Experiments performed in our laboratory confirm the presence of 50 kHz - 5 MHz predominantly axial instabilities in the plume – a result supported by our numerical simulations (see Fig. 4) [21, 22]. These instabilities are strong, and are well-defined by a limited bandwidth in frequency and wavenumber. As a consequence, it is hypothesized that these instabilities are coherent (not turbulent), and could be responsible for the electron mobility. Furthermore, these instabilities are principally located at the exit plane and in the near-field plume of the Hall thruster, an area where wall-effects are unlikely to explain the mobility. A theory has been developed to explain the transport caused by instabilities of this type [23]. Previous work on fluctuation-induced transport has considered azimuthal instabilities only – though our experimental and numerical results indicate a mixed propagation vector. If the primary instabilities have a strong axial component, they can grow and pass through the region where they experience strong gain before they saturate. As they leave the thruster they should dissipate, and not lead to turbulence. To date, results indicate that coherent fluctuations in the potential (though only a few eV), with a modest axial propagation vector, are capable of explaining the electron mobility in the Hall-effect thruster (see Fig. 5). Furthermore, the multi-MHz axial instabilities observed in numerical simulations can explain the anomalous transport at the exit plane. Further tests are necessary to characterize the power spectral density of fluctuations in the Hall thruster at high frequencies, but our results suggest that axial instabilities are a possible explanation for the observed mobility at low discharge voltage near the exit plane, and in the near-field plume region of the Hall thruster.

2.1.2 Novel Near-Field Diagnostics.

Under the auspices of this past grant, we have developed two new non-intrusive diagnostics for the near-field of Hall thrusters – a region where transport cannot be
attributed to wall collisions, and a region where electron and ion dynamics is poorly understood.

These diagnostics were implemented and transferred to the Air Force Research Laboratory (AFRL) at Edwards Air Force Base, for studying the near-field of a BHT-200 low power Hall thruster (Fig. 6 - top). The novel diagnostics methods – millimeter-wave microwave interferometry [24-26], and vacuum ultraviolet (VUV) absorption spectroscopy [27] have revealed the presence of a very complex plasma flow never before captured in either previous intrusive probe-based measurements, or in recent numerical simulations. The microwave interferometry maps out the ion density field, which will be greatly impacted by the flow acceleration pattern as the ions respond to the local electric field distribution, shaped largely by the local magnetic field. The VUV absorption spectroscopy provides a mapping of the neutral xenon number density, and varies in the near field as a result of the injection of neutral xenon from the cathode, and the re-ingestion of xenon from the chamber environment, since ground test facilities cannot reproduce the ideal vacuum of the space environment. Both measurements have given us an unprecedented “picture” of the near-field, which has been generally elusive, since electrostatic probe measurements interfere with the operation of the thruster when immersed so close to the acceleration zone.

The unique feature of the system developed during this grant is that this interferometer operates at 90 GHz, allowing the beam to be focused in size to a waist of less than a centimeter. The beam is passed through a series of paths across the thruster plume, and, from the measured phase-shift detected by each pass, a three-dimensional reconstruction of the plasma (electron or ion) density is projected onto a computer. An image of the spatial variation in the plasma density, superimposed onto a photograph of the thruster, is shown in Fig. 6 - bottom. Evident is the presence of a toroidal plasma distribution, reminiscent of the annular discharge from which the plasma is generated. However, also apparent is a strong depression in the plasma density along the thruster axis – a feature not previously seen by any other diagnostic. This low density depression is attributed to the local acceleration of the ions due to the electric field generated by the convergence of the magnetic fields on the thruster axis. It coincides with the region of strong emission seen in Hall thruster photographs (the so-called “axial spike”), and recent electron kinetic analysis (see Sec ##) indicate that this also coincides with a region of high electron temperature. The physics of this region of the plasma is still poorly understood, and in the proposed studies, we intend to carry out particle-in-cell simulations of the plasma near-field. The particular interferometer design

Figure 6. Top: photo showing operating thruster. Bottom: photo of thruster with measured plasma density field superimposed.
also permits the detection of real-time fluctuations in the path-averaged plasma density. This secondary feature has proved to be an important method for quantifying plasma fluctuations in these thrusters, as they are known to be quasi-stable, sometimes exhibiting large discharge current fluctuations under certain operating conditions.

VUV absorption spectroscopy is not uncommon in plasma diagnostics. However, the approach developed under this grant is a unique variation, which does not require an external VUV light source. In this variant [27], the VUV emission generated by the thruster plasma itself is redirected back though the plasma and is absorbed by the plasma on its second pass. When detected, it is compared to the intrinsic emission (that is not redirected through the plasma). The ratio of the intrinsic emission and redirected and absorbed emission is proportional, to a great extent, to the path-averaged ground state xenon density. By passing this emission through various chords across the plume, a mapping of the path-averaged ground-state density is generated. In principal, one can reconstruct a three-dimensional image very much like the CAT scan used in the microwave interferometer, but the theory for this reconstruction is still under development. A mapping of the near-field xenon density is shown in Fig. 7. A schematic of the thruster and cathode positioning is superimposed for reference. Note that this map is of the density-path length product, and an inversion of the data for radial variation in the neutral density must be carried out. This inversion algorithm development is part of the next phase of the research.

Both the millimeter-wave interferometry and VUV absorption spectroscopy offer quantitative visualizations of the thruster plasma never before seen. These measurements provide a test-bed for the complex flow expected in this region. The millimeter-wave diagnostics will be further refined for measurements in the near-field of the external acceleration molecular propellant thruster, described in below.

2.1.3 Wall-less Hall Thrusters
Magnetic Interference Hall Accelerator

Two years ago, we discovered that under certain operating conditions, the acceleration zone of a Hall thruster can be moved to be completely outside of the channel [28 29]. This surprising result led to the concept of a "wall-less" thruster, where the shape of the magnetic field gives rise to ionization and confinement of electrons beyond the vicinity of propellant-confining surfaces or pole pieces. During the past year, we have designed and fabricated a thruster - the Magnetic Interference Hall Accelerator (MIHA), which brings us close to this ideal concept (see Fig. 8). This thruster also provides a

Figure 7. Color map of neutral density-path length field near the exit of the BHT-200 Hall thruster, measured by VUV absorption spectrometry. Note that the chamber pressure was 6.7 x 10⁻⁵ Torr for these measurements.
platform to examine anomalous transport in the absence of a conventional ceramic channel. In this thruster, the impact of near-wall transport is mitigated.

MIHA is made possible by a magnetic circuit whose contours form a virtual channel, which serves to replace the ceramic channel in vacuum, and aims to accomplish many of its previous functions (see Fig. 9). The discharge is focused through a region of high magnetic field located outside the exit plane of the thruster, where the tight cyclotron orbit of the electron inhibits its mobility. The electric field is highest where the electron mobility is lowest, so, ions are accelerated in this region. High-energy sputtering is reduced – since acceleration is accomplished beyond the thruster's propellant channel (see Fig. 10). To help focus ions towards the discharge centerline, the shape of the magnetic field is that of a plasma lens. To manage electron transport, the intensity of the magnetic field increases off the discharge centerline. This causes the magnetic field to act like a funnel for electrons, which confines the electrons in a manner analogous to that in a magnetic bottle. A well-focused discharge is achieved.

In experiments, MIHA is found to operate like a conventional Hall-effect thruster. It demonstrates a reduction in its discharge current with an increase in B, and displays a strong Hall 'breathing-mode' in certain operational regimes. The ionization efficiency has not been measured, and is probably less than that of a single-stage coaxial thruster (since the residence time of a neutral is shorter), but this can be overcome by staging, and by increasing the size of the thruster. Tests to measure performance are ongoing, and will be reported on at the 2006 JPC [30].

It should be remarked that the design of MIHA was flexible, and allowed for considerable modification of its magnetic field. It was found that the primary deficiency of the linear thruster – that of its open electron drift – can be partially overcome by MIHA, if an inflection in the E × B drift is forced. In the conventional linear Hall thruster, the single-direction E × B drift results in a strong flux of electrons to the side wall. These electrons experience scattering, and this causes the electron mobility to be high. With MIHA, the thruster can be operated with a strong E × B...
drift and good electron confinement, but include a reversal of the drift right before the anode (since the direction of the magnetic field can be reversed over a small spatial scale). This reduced the electron flux to the wall, and the effect was visually apparent — the glow at the side wall was markedly reduced. In this mode, it is found that the discharge current for MIHA can be decreased at the same discharge voltage, even if the peak magnetic field is reduced (by choosing a more optimal shape for the magnetic field). This effect will be detailed more precisely in future studies.

2.1.4 Thruster Simulations

Hall thruster simulations have the potential to greatly shorten the time towards space qualification by reducing (and possibly eliminating) the need for many costly ground-based life tests. Efforts in the development of robust simulations have continued under this past grant period, focused mainly on two fronts: (i) the integration into the simulations of realistic and physical transport models [31, 32], and (ii) the inclusion in these simulations many physical phenomenon that are critical to the thruster wear process permitting the prediction of the concomitant wall erosion (recession) over thruster lifetime. The simulations are of a hybrid nature — modeling the electrons as a fluid, and the neutrals and ions as particles using a Monte-Carlo PIC formalism [33]. Recently, we have added molecular collisions in three dimensions, as well as the ingestion of background gas from the chamber and cathode [34]. With an accurate model of the interaction of neutral particles and ions with the walls to cause sputtering [35, 36], we have been able to predict the erosion behavior and life expectancy of our laboratory Hall thruster. The simulations can capture the unsteady behavior in the plasma in two dimensions (axial and radial — because of the 2D electron fluid constraint), such as instabilities that give rise to high frequency fluctuations. These fluctuations can enhance non-local electron transport, which in part controls the plasma resistivity. The neo-
classical transport models described above are now being added into these simulations. Physical modeling the resistivity is important, as it determines the electric field distribution which, in turn, controls the ion energy and trajectory, which ultimately determines which ions strike the confining engine walls, leading to wall erosion.

An example output of the simulation is depicted in Fig. 11. The figure depicts the ion density distribution within our laboratory Hall thruster, and superimposes their average velocity. Figure 12 is a depiction of the predicted time evolution of the inner and outer annular walls of the channel of this thruster. As evident, most of the erosion takes place in the last 5 mm of the channel, in the region very near where the ions have experienced much of their acceleration. It is noteworthy that the plasma properties are recalculated after every surface advancement, to predict the effect that the reshaped channel may have on thruster performance.

Continuing research focuses on enhancing and expanding these simulation capabilities, as described in Sec. 3.2.4, including extending the simulations to the axial-azimuthal domain, preliminary results of which were presented recently [37-39]. As part of this new project, we will examine the feasibility of extending these hybrid simulations to quasi-3D, for simulating the co-axial MIHA thruster. These hybrid simulations will be compared to the results of full fluid simulations which we also propose to undertake (first in 2D), and will also be used to generate the near-field electric potential for the 3D non-local electric kinetic simulations which are under development and described in Sec. 3.2.4.

2.1.5 Ultra-Low Power Hall Thrusters.

During the past year, we have embarked on an effort to greatly push the envelope of miniaturization of Hall thrusters. Based on our understanding of transport and wall heating in Hall thrusters, we advanced the reduction in scale of these thrusters to "ultra-low power" levels [40]. The goal is to design and test a 1 W Hall thruster capable of operating at a specific impulse of 1000 seconds, and at 20% efficiency, on easily storable propellants. Such a thruster could be integrated into a picosatellite, which can provide as much as 10-20W of power with expandable solar panels.
The challenges facing the development of such ultra-low power Hall thrusters are formidable. The smaller size necessarily requires better volume confinement of the electrons, achieved by much stronger magnetic fields. Attempts to scale down Hall thrusters below 100W require some introduction of permanent magnets as opposed to the more widely used electromagnetic circuits for field generation in the larger designs. It is also well known that the heat-flux experienced by the thruster plasma chamber increases significantly with diminishing size, putting a significant thermal stress on thruster components.

During this past year, we have successfully operated a thruster with an annular channel of 500 micrometers in width and a channel diameter of only 3.5 millimeters [40-42]. The magnetic circuit is constructed entirely out of SmCo permanent magnets with a central iron pole piece. A photograph of the thruster is shown in Fig. 13. The thruster was operated over a range of 10W – 30W. These first tests revealed some interesting findings such as the importance of thermal management, and the placement and performance of the cathode. A major accomplishment was the introduction of thick film diamond as a heat spreader for the central pole piece. The precise nature of the mechanism for heat loading on the central pole-piece is not known, but, based on the erosion pattern of the diamond cover, is believed to be due to intense focusing of plasma electrons, as there is a convergence of magnetic field lines on the central axis of the thruster. Preliminary measurements of performance suggest that this thruster operates at between 8 and 15% efficiency - below the targeted efficiency, and the ion beam had a greater divergence than anticipated. The low efficiency and high beam divergence is attributed to a non-ideal magnetic field configuration – an improved version of which will be introduced to a second generation thruster currently under construction. We also found that cathode design and placement greatly affects efficiency. Preliminary tests of a microwave plasma cathode are ongoing, as are tests of carbon-dioxide as a possible propellant, which can be stored as a sublimable solid.

**Synopsis:** As indicated below, this prior grant was highly leveraged, involving a total of six Ph.D. students (most of which are supported through either Stanford (Stanford Graduate Fellowship) or external sources (NSF, NDSEG). Many of these students will stay on and work on the subject matter of the continuing grant (Knoll, Smith, Allis, and
Poehlmann). The grant also supplied partial support for one research associate (Gascon) and one post-doctoral student (Ito). Throughout the two years, five undergraduates were (some continue to be) involved, many of which co-authored publications. Finally, for the first time, we have hosted the participation of a high-school student M. Bachand, during the summer of 2005. Mr. Bachand was recently accepted to Stanford, MIT, and Princeton. His experience in our laboratory constructing a retarding potential analyzer and carrying out measurements played heavily into his decision to pursue engineering as a career.

During this two and one-half year period, twenty-one papers were published, and there are seven papers that are in preparation or have been submitted for peer-reviewed publication.

2.2 Personnel Supported

Professor: M. Cappelli (P.I.)
Graduate Students: N.B. Meezan (with partial Stanford support SGF), C. Thomas (with partial Stanford support SGF), M. Allis (full external support NSF), A. Knoll, A. Smith (full external support NDSEG), and F. Poehlmann (with full Stanford support SGF).
Post-Doctoral Associate: N. Gascon (partial external support), T. Ito (full external support)
Undergraduate Student: R. Norte, W. Hermann, M. Kodiak, M. Mowers, C. Kish
Visiting Student: M. Bachand
Visiting Researcher: E. Sommier

2.3 Dissemination of Information

Publications or Published Abstracts Resulting Directly from this Grant


Unpublished Conference Presentations


Peer-Reviewed Archival Papers in Preparation or Submitted


3. References


