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14. ABSTRACT

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.

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Final Technical Report
Air Force Office of Scientific Research
Grant # FA9550-04-1-0122

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For:

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Air Force Office of Scientific Research

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 Al_2O_3 wall of the discharge

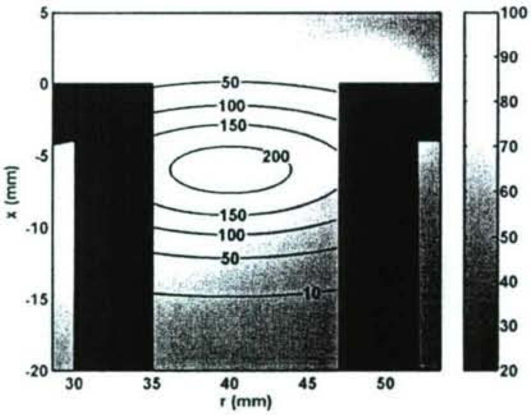

Figure 2. The average azimuthal drift current density (contours, in kA/m^2) and |B|, in Gauss, (accounting for current perturbations) for the 200V discharge.

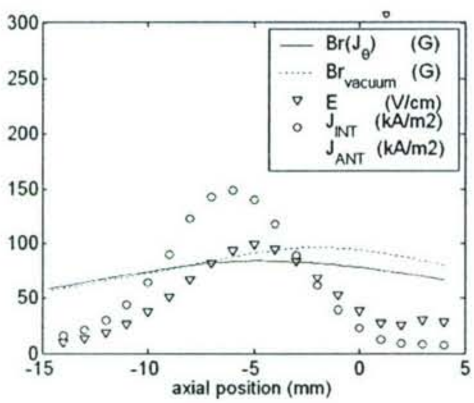

Figure 3. Channel centerline properties for the 200V discharge.

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.

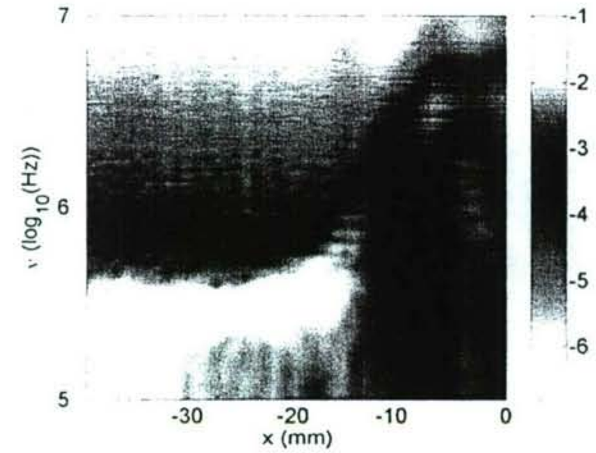

Figure 4.The power spectral density in log10 scale of axial instabilties witnessed in numerical simulation.

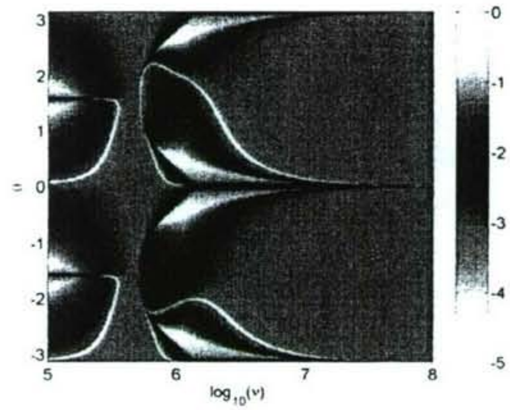

Figure 5. The relative axial transport in log10 scale affected by a 1eV fluctuation in potential at x = -10 mm.

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 instabilties 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 instabilties 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 instabilties 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 instabilties 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 instabilties 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

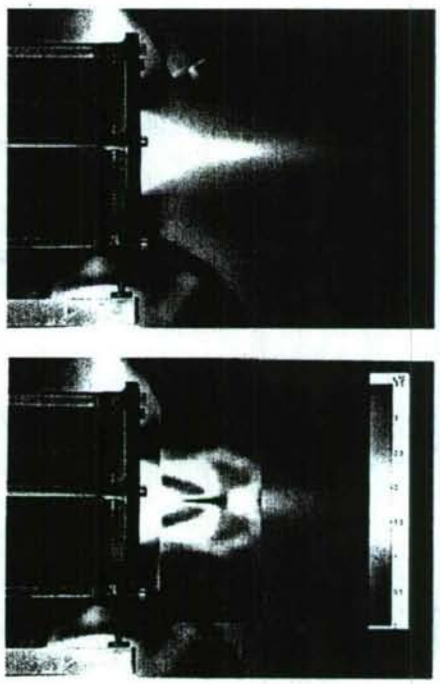

Figure 6. Top: photo showing operating thruster. Bottom: photo of thruster with measured plasma density field superimposed.

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.

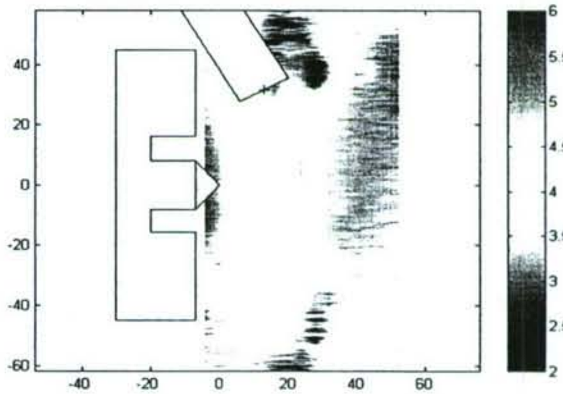

Figure 7. Color map of neutral density-path length field near the exit of the BHT-200 Hall thruster, measured by VUV absorption spectrometry. Note that the chamber pressure was 6.7 x 10^{-5} Torr for these measurements.

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

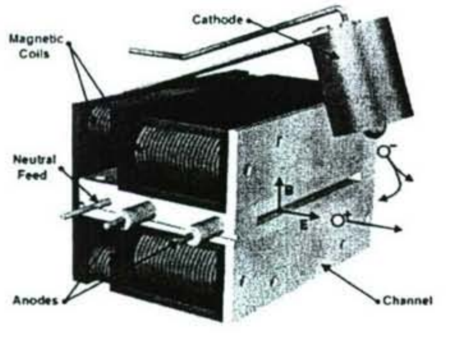

Figure 8. Diagram of MIHA.

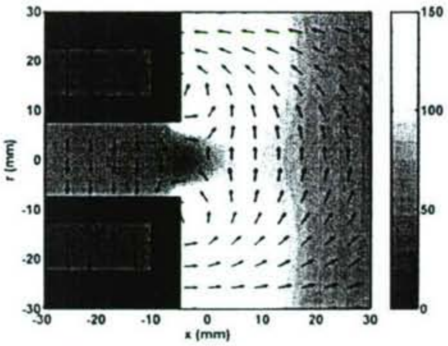

Figure 9. MIHA magnetic field.

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

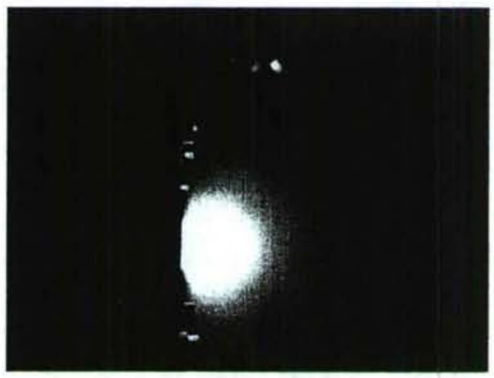

Figure 10. MIHA in operation at 160V

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

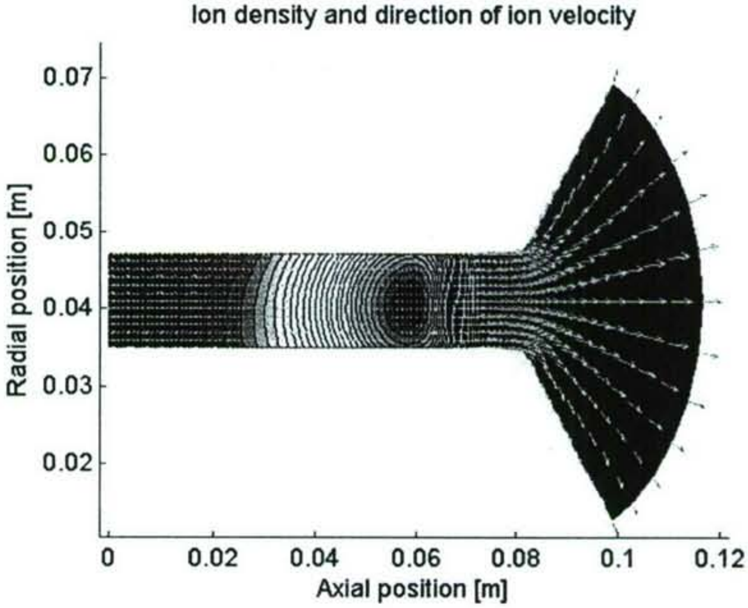

Figure 11. Ion density (color map) and average ion velocity (arrows).

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-

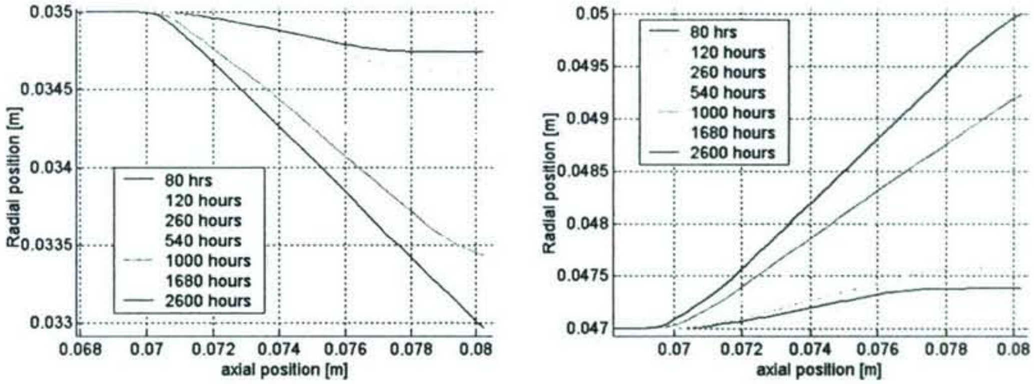

Figure 12. Predicted erosion history (wall evolution). LEFT – inner wall, RIGHT – outer wall.

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 at 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.

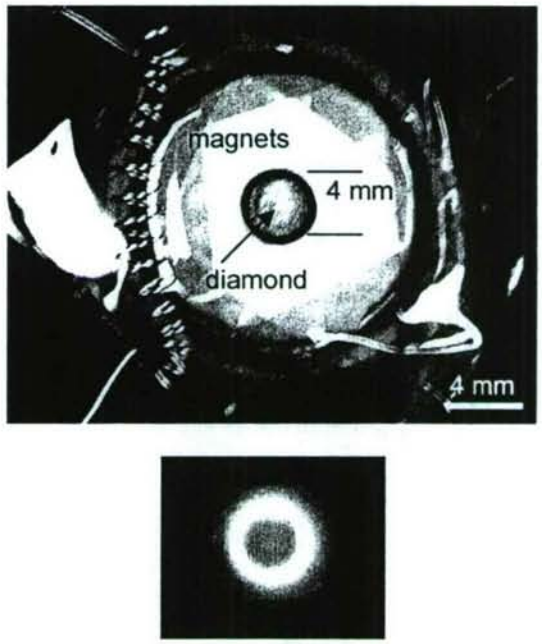

Figure 13. Top: photo showing thruster details. Bottom: photo of operating thruster (same scale as top).

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

C. Thomas, N. Gascon, and M. Cappelli, "Spatial and Temporal Mapping of Azimuthal Drift Current in a Hall Thruster," AIAA-2003-4854, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.

N. Gascon, N. Meezan, C. Thomas and M. Cappelli, "Plasma Oscillations and Wall Material Effects in a Hall Thruster," AIAA-2003-4857, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.

N. Gascon, C. Thomas and M. Cappelli, AIAA-2003-5156 "Further Studies of a Linear Hall Thruster", 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.

M. Cappelli, W. Hermann, M. Kodiak, N. Gascon, and W. Hargus, Jr., "A 90 GHz Phase-Bridge Interferometer for Plasma Density Measurements in the Near Field of a Hall Thruster," AIAA-2004-3775, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

M. Cappelli and W. Hargus, Jr., "Images of Ground State Xenon in the Near Field of a Low Power Hall Thruster," AIAA-2004-4120, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

M. Allis, N. Gascon, C. Vialard-Goudou, M. Cappelli, and E. Fernandez, "A Comparison of 2-D Hybrid Hall Thruster Model to Experimental Measurements," AIAA-2004-3951, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

C. Thomas, N. Gascon, and M. Cappelli, "Non-Intrusive Characterization of the Hall Thruster Azimuthal Drift Current," AIAA-2004-3776, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

N. Gascon, M. Allis, C. Thomas, M. Cappelli, and E. Fernandez, "A Closer Look at Longitudinal Oscillations Inside a Hall Thruster," AIAA-2004-3780, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

N. Gascon, C. Thomas, M. Cappelli, and D. White, "Fifty Hour Wear Test of a Linear Hall Thruster with Boron Nitride and Diamond Walls," AIAA-2004-4229, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

M.K. Allis, C.A. Thomas, N. Gascon, M.A. Cappelli, and E. Fernandez, "Electron Cross-Field Transport in 2D Hybrid Hall Thruster Simulation," Abstract 10529, 32nd IEEE International Conference on Plasma Sciences, Monterey, CA, June 18-23, 2005.

C. Thomas and M. Cappelli, "Gradient transport processes in E x B plasmas", AIAA-2005-4063, , 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10 - 13 July 2005, Tucson, Arizona.

G. Reed, W. Hargus, and M. Cappelli, "Microwave Interferometry (90 GHz) for Hall Thruster Plume Density Characterization" AIAA-2005-4399, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10 - 13 July 2005, Tucson, Arizona.

N. Gascon and M. Cappelli, and W. Hargus, "Ion Velocity Measurements in a Linear Hall Thruster," AIAA-2005-4401, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10 - 13 July 2005, Tucson, Arizona.

M.K. Allis, N. Gascon, M.A. Cappelli, and E. Fernandez, "Effect of Charge Exchange on 2D Hall Thruster Simulation", IEPC-2005-057, Proceedings of the 29th International Electric Propulsion Conference, Princeton, NJ, Oct. 31-Nov. 4, 2005

N. Gascon, R. Corey, M. Cappelli, and W. Hargus, "Hall thruster with an external acceleration zone," IEPC 2005-196, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, NJ, Oct. 31- Nov. 4, 2005.

E. Sommier, M. Allis, and M. Cappelli, "Wall erosion in 2D Hall Thruster Simulation", IEPC 2005-189, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, NJ, Oct. 31- Nov. 4, 2005.

T. Ito, N. Gascon, W. S. Crawford, M. A. Cappelli, "Ultra-Low Power Stationary Plasma Thruster", IEPC-2005-198 Proceedings of the 29th International Electric Propulsion Conference, Princeton, NJ, October 31 – November 4, 2005.

E. Fernandez, A. Knoll, N. Gascon, M. Cappelli, T. Kaya, "A Two-dimensional (z-theta) Hybrid Simulation of Coaxial Hall Thrusters", IEPC 2005-197, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, October 31 November 4, 2005.

F. Poehlmann, N.Gascon, C. Thomas, and M. Cappelli, "The coaxial high energy thruster," IEPC 2005-100, Proceedings of the 29th International Electric Propulsion Conference, Princeton, NJ, October 31 – November 4, 2005.

Unpublished Conference Presentations

E. Fernandez, N. Borelli, M. Cappelli, N. Gascon, "Investigation of Fluctuation-Induced Electron Transport in Hall Thrusters with a 2D Hybrid Code in the Azimuthal and Axial Coordinates, 45th Annual Meeting of the Division of Plasma Physics, Albuquerque, New Mexico, October 27-31, 2003.

T. Ito, M. A. Cappelli, "Development of Micro Hall Thruster", 58th Gaseous Electronics Conference, San Jose, California, USA, October 16-20, 2005.

Peer-Reviewed Archival Papers in Preparation or Submitted

T. Ito and M. A. Cappelli, "A Low Power Magnetized Microdischarge Ion Source", Appl. Phys. Lett. **89**, 061501, 2006.

M. A. Cappelli, N. Gascon, and W. A. Hargus Jr., "Millimetre wave plasma interferometry in the near field of a Hall plasma accelerator" J. Phys. D: Appl. Phys. **39**, 4582, 2006.

M. K. Scharfe, N. Gascon, M. A. Cappelli, and E. Fernandez, "Comparison of Hybrid Hall Thruster Model to Experimental Measurements," Phys. Plasmas **13**, 083505 (2006).

E. Sommier, M.K. Scharfe, N. Gascon, and M. Cappelli, "Wall Erosion in 2D Hall Thruster Simulations", submitted to *J. Propulsion and Power*, 2006.

C. A. Thomas, N. Gascon, and M. A. Cappelli, "Nonintrusive characterization of the azimuthal drift current in a coaxial E x B discharge plasma" Physical Review E **74**, 056402, 2006..

N. Gascon, M.A. Cappelli, and W. Hargus, Jr., "The Structure of the Near-Field of a Linear Geometry Hall Discharge with External Ion Acceleration", submitted to *Plasma Sources Science and Technology*, 2007.

3. References

1. N. Gascon, C. Thomas, M. Cappelli, and D. White, "Fifty Hour Wear Test of a Linear Hall Thruster with Boron Nitride and Diamond Walls," AIAA-2004-4229, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004
2. N.B. Meezan, N. Gascon, and M. A. Cappelli, "Linear geometry Hall thruster with boron nitride and diamond walls", IEPC-01-39, 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October 2001.
3. Manzella, D., Yim, J., Boyd, I., "Predicting Hall thruster operational lifetime," AIAA 2004-3953, 40th AIAA Joint Propulsion Conference, Fort Lauderdale, FL, July 11–14, 2004.E.
4. E. Sommier, M. Allis, and M. Cappelli, "Wall erosion in 2D Hall thruster simulation", IEPC 2005-189, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, NJ, Oct. 31- Nov. 4, 2005.
5. E. Sommier, M.K. Scharfe, N. Gascon, M.A. Cappelli, and E. Fernandez, "Predicting plasma-induced Hall thruster wall erosion with two-dimensional hybrid simulations," submitted to Phys. Plasmas, January, 2007.
6. Morozov A.I., Melikov I.V., "Similitude in Hall-current plasma accelerators", Sov. Phys. Tech. Phys., 19, 340, 1974.
7. N.B. Meezan, W.A. Hargus, Jr., and M.A. Cappelli, "The anomalous electron mobility in a coaxial Hall discharge plasma" Phys. Rev. E 63, 026410-1-026410-7, 2001.
8. N.B. Meezan and M.A. Cappelli, "Kinetic study of wall collisions in a Hall thruster," Physical Review E 66, 036401, 2002.

9. M. A. Cappelli, N.B. Meezan, and E. Chesta, "Fluctuation-induced electron transport in closed-drift Hall discharges," 27th IEEE International Conference on Plasma Science, New Orleans, LA, June 4-7, 2000. See also Proceedings Record, pg. 187.
10. C. Thomas and M. Cappelli, "Gradient transport processes in E x B plasmas", AIAA-2005-4063, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10 - 13 July 2005, Tucson, Arizona.
11. M. A. Cappelli, N.B. Meezan, and N. Gascon, "Transport physics in Hall plasma thrusters" AIAA-2002-0485, Aerospace Sciences Meeting, Reno, NV, January 2002.
12. M. Scharfe, C. Thomas, N. Gascon and M. Cappelli, "Shear- based model for electron transport in 2D hybrid Hall thruster simulations", AIAA-2007-5208, 43rd AIAA Joint Propulsion Conference, July 9 – 11, Cincinnati, OH, 2007.
13. J. Fox, O. Batishchev, and M. Martinez-Sanchez, "Kinetic model of anomalous transport for Hall effect thrusters", 48th Annual Meeting of the Division of Plasma Physics, October 30–November 3, Philadelphia, PA, 2006.
14. E. Fernandez, A. Knoll, and M. A. Cappelli, "An axial- azimuthal hybrid simulation of coaxial Hall thrusters," AIAA 2006-4329, 42nd AIAA Joint Propulsion Conference," July 9 - 12, Sacramento, CA, 2006.
15. A. Knoll, N. Gascon and M. Cappelli, "Numerical simulation of high frequency wave coupling within a Hall thruster," AIAA-2007-5266" 43rd AIAA Joint Propulsion Conference, July 9 – 11, Cincinnati, OH, 2007.
16. A. Smith and M. Cappelli, Near- field potential structure of Hall thrusters: experimental investigation and numerical interpretation," AIAA-2007-5240, 43rd AIAA Joint Propulsion Conference, July 9 – 11, Cincinnati, OH, 2007.
17. C. Thomas, N. Gascon, and M. Cappelli, "Non-Intrusive Characterization of the Hall Thruster Azimuthal Drift Current," AIAA-2004-3776, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.
18. C. Thomas, N. Gascon, and M. Cappelli, "Spatial and Temporal Mapping of Azimuthal Drift Current in a Hall Thruster," AIAA-2003-4854, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.
19. C. A. Thomas, N. Gascon, and M. A. Cappelli, "Nonintrusive characterization of the azimuthal drift current in a coaxial E x B discharge plasma" Physical Review E 74, 056402, 2006.
20. N.B. Meezan and M.A. Cappelli, "Kinetic study of wall collisions in a Hall thruster," Physical Review E 66, 036401, 2002.
21. N. Gascon, N. Meezan, C. Thomas and M. Cappelli, "Plasma Oscillations and Wall Material Effects in a Hall Thruster," AIAA-2003-4857, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.
22. N. Gascon, M. Allis, C. Thomas, M. Cappelli, and E. Fernandez, "A Closer Look at Longitudinal Oscillations Inside a Hall Thruster," AIAA-2004-3780, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.
23. Cliff A. Thomas "Anomalous electron transport in the Hall effect thruster, Ph.D. Thesis, Department of Mechanical Engineering, Stanford University, 2007.
24. M. Cappelli, W. Hermann, M. Kodiak, N. Gascon, and W. Hargus, Jr., "A 90 GHz Phase-Bridge Interferometer for Plasma Density Measurements in the Near Field of a Hall Thruster," AIAA-2004-3775, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.

25. G. Reed, W. Hargus, and M. Cappelli, "Microwave Interferometry (90 GHz) for Hall Thruster Plume Density Characterization" AIAA-2005-4399, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10 - 13 July 2005, Tucson, Arizona.
26. M. A. Cappelli, N. Gascon, and W. A. Hargus Jr., "Millimetre wave plasma interferometry in the near field of a Hall plasma accelerator" J. Phys. D: Appl. Phys. 39, 4582, 2006.
27. M. Cappelli and W. Hargus, Jr., "Images of Ground State Xenon in the Near Field of a Low Power Hall Thruster," AIAA-2004-4120, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.
28. N. Gascon, R. Corey, M. Cappelli, and W. Hargus, "Hall thruster with an external acceleration zone," IEPC 2005-196, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, NJ, Oct. 31- Nov. 4, 2005.
29. N. Gascon and M. Cappelli, and W. Hargus, "Ion Velocity Measurements in a Linear Hall Thruster," AIAA-2005-4401, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 10 - 13 July, Tucson, AZ, 2005.
30. C. Thomas, E. Sommier, N. Gascon, and M. Cappelli, "The magnetic interference Hall accelerator," AIAA-2006-4993, 42nd AIAA Joint Propulsion Conference," July 9 - 12, Sacramento, CA, 2006.
31. M. Allis, N. Gascon, C. Vialard - Goudou, M. Cappelli, and E. Fernandez, "A Comparison of 2-D Hybrid Hall Thruster Model to Experimental Measurements," AIAA-2004-3951, 40th Joint Propulsion Conference, Ft. Lauderdale, FL July 11-14, 2004.
32. M.K. Allis, C.A. Thomas, N. Gascon, M.A. Cappelli, and E. Fernandez, "Electron Cross-Field Transport in 2D Hybrid Hall Thruster Simulation," Abstract 10529, 32nd IEEE International Conference on Plasma Sciences, Monterey, CA, June 18-23, 2005.
33. M. K. Scharfe, N. Gascon, M. A. Cappelli, and E. Fernandez, "Comparison of Hybrid Hall Thruster Model to Experimental Measurements," *Phys. Plasmas*, submitted April, 2006.
34. M.K. Allis, N. Gascon, M.A. Cappelli, and E. Fernandez, "Effect of Charge Exchange on 2D Hall Thruster Simulation", IEPC-2005-057, 29th International Electric Propulsion Conference, Princeton, NJ, Oct. 31-Nov. 4, 2005
35. E. Sommier, M. Allis, and M. Cappelli, "Wall erosion in 2D Hall Thruster Simulation", IEPC 2005-189, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, NJ, Oct. 31- Nov. 4, 2005.
36. E. Sommier, M.K. Scharfe, N. Gascon, and M. Cappelli, "Wall Erosion in 2D Hall Thruster Simulations", in preparation for *J. Spacecraft and Rockets*, 2006.
37. E. Fernandez, A. Knoll, N. Gascon, M. Cappelli, T. Kaya, "A Two-dimensional (z-theta) Hybrid Simulation of Coaxial Hall Thrusters", IEPC 2005-197, Proceedings of the 29th International Electric Propulsion Conference, Princeton University, October 31 November 4, 2005.
38. E. Fernandez, N. Borelli, M. Cappelli, N. Gascon, "Investigation of Fluctuation-Induced Electron Transport in Hall Thrusters with a 2D Hybrid Code in the Azimuthal and Axial Coordinates, 45th Annual Meeting of the Division of Plasma Physics, Albuquerque, New Mexico, October 27-31, 2003.

39. E. Fernandez, A. Knoll, and M. A. Cappelli, "An axial- azimuthal hybrid simulation of coaxial Hall thrusters," AIAA 2006-4329, 42nd AIAA Joint Propulsion Conference," July 9 - 12, Sacramento, CA, 2006.
40. T. Ito, N. Gascon, W. S. Crawford, M. A. Cappelli, "Ultra-Low Power Stationary Plasma Thruster", IEPC-2005-198 Proceedings of the 29th International Electric Propulsion Conference, Princeton, NJ, October 31 – November 4, 2005.
41. T. Ito, M. A. Cappelli, "Development of Micro Hall Thruster", 58th Gaseous Electronics Conference, San Jose, California, USA, October 16-20, 2005.
42. T. Ito and M. A. Cappelli, "A Low Power Magnetized Microdischarge Ion Source", Appl. Phys. Lett. 89, 061501, 2006.