Overview of U.S. Academic Programs in Electric Propulsion

Compiled and Edited by

E.Y. Choueiri*
Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL)
MAE Dept.
Princeton University
Princeton, New Jersey 08544

AIAA-99-2163 †

Abstract

We present an overview of recent electric propulsion research activities carried out by twelve research groups at US academic institutions. The groups are at: Colorado State University, Cornell University, Massachusetts Institute of Technology, Ohio State University, Pennsylvania State University, Princeton University, Stanford University, University of Illinois at Urbana-Champaign, University of Michigan, University of Southern California and Worcester Polytechnic Institute The research activities are sponsored by NASA, DoD, DoE and other governmental agencies and industrial partners and include experimental, analytical and numerical work related to: ion thrusters, plasma contactors, colloidal thrusters, Hall thrusters, ablative and gas-fed pulsed plasma thrusters, magnetoplasmadynamic thrusters, arcjets, microwave-heated thrusters, field emitter array cathodes, micropropulsion, thruster plumes and tethers.

1 Colorado State University

Work at Colorado State University over the past year in areas related to electric propulsion has focused on understanding events that accompanied the tether failure during the TSS-1R electrodynamic tether mission and on increasing ion thruster grid lifetimes by reducing the sputter yields of grid materials. A new concept in plasma contacting has evolved from the former effort.

Plasma Contacting with a Solid Expellant. The break on the tether during the second electrodynamic tether mission (TSS-1R) was followed by a highly unusual, yet efficient electron emission (plasma contacting) process from the broken end of the tether to the ambient space plasma. Experiments and analyses have been conducted which illustrate the important physical processes required for such a plasma contacting process to occur. Specifically, it has been shown that 1) a dense plasma discharge can be sustained by ionization of decomposed tether (primarily Teflon) vapors and 2) charge transport between the small strands of copper wire and a high density plasma that develops immediately adjacent to the wire occurs primarily via ions collected on the wire. The series of experiments and analyses that led to these conclusions and show that thermionic and/or field emission were not the mechanisms for direct electron emission from the wire are described in ref. [1]. Further analysis suggested a current conduction mechanism similar to that observed in liquid mercury cathodes where intense ionization occurs near the cathode and current continuity is achieved via ions collected on the cathode and to a lesser extent by secondary electrons emitted from it. Experiments were also conducted in which operation of hollow cathodes on vaporized Teflon at performance levels similar to those of cathodes operating on xenon was demonstrated. Normal operation was realized even when these cathodes were made of copper and when they were held near ambient temperatures. A

*Chief scientist at EPPDyL. Assistant Professor, Applied Physics Group, MAE Dept. and Associated Faculty at the Dept. of Astrophysical Sciences. Senior Member AIAA.

†Presented at the 35^{th} AIAA Joint Propulsion Conference, Los Angeles, CA, June 21-23, 1999.

plasma contactor that operates on an inert solid expellant like Teflon is desirable because the mass and complexity of a gaseous expellant feed/storage system is eliminated.

Ion Implantation to Reduce the Sputter Yields of Thruster Grids. Ion thruster grid lifetimes are generally limited by ion sputtering. Sputter yields of nitrides and carbides of typical grid materials are lower than those of the pure materials. These compounds can be produced by implanting fabricated grids with nitrogen or carbon while they are being held at temperatures where these implants will diffuse rapidly through thicknesses that will typically be of the order of 0.5 mm. Experimental results suggest the implanted elements will diffuse rapidly (a few hours) via grain boundaries provided temperatures are maintained at levels where diffusion rates are equal to or greater than implantation supply rates. Lattice diffusion into grains, which have a dimension near 3 mm in a typical molybdenum grid material, is slower. Measurements made to date show implantation of molybdenum with nitrogen (at $\simeq$550 °C) and carbon (at $\simeq$900 °C) induce 15% and 40% reductions in sputter yield, respectively, even though times and temperatures were such that negligible lattice diffusion had occurred.

2 Cornell University[1]

Device Modeling. The purpose of device modeling studies in general is to try to improve device performance and to provide boundary conditions for plume computations. Presently the activities consist of modeling of the internal flows of ion thrusters, Hall thrusters, and Teflon-fed pulsed plasma thrusters.

The Hall thruster modeling is being conducted in collaboration with a research group in Toulouse, France. The PPT work is in support of plume studies discussed below. Several papers on these investigations will be presented at the upcoming IEPC meeting in Japan.

A study of current collection on the acceleration grid of the UK-10 ion thruster is conducted in collaboration with the Aerospace Corporation[2]. A particle approach is employed to model the plasma dynamics and collision phenomena. Xenon atoms, single ions, and double ions are simulated. Momentum transfer, charge exchange, and Coulomb collisions are all included in the computer model. The significance of the results is that the computational model developed is able to successfully predict the accel grid current over a wide range of operating conditions. It is found that charge exchange ions account for only about 20% of the accel current and Coulomb collisions have no effect at all. A full description of the model and results is provided along with new experimental data in ref. [2].

Plume Modeling The purpose of plume modeling studies is to assess spacecraft integration issues such as contamination and sputtering. In the last year, we have conducted plume analyses for a range of devices including Hall thrusters, arcjets, and Teflon-fed PPT's.

The Hall thruster work is focused on improving the physical modeling through use of detailed experimental data taken primarily by the PEPL group at the University of Michigan (see Section 10). The effects of electron temperature, magnetic field, and vacuum chamber are being studied. Results are presented in ref. [3]. The arcjet work involved computing the plume from a Primex hydrazine arcjet. The work was performed in conjunction with the Aerospace Corporation. Two papers on this study will be presented at the IEPC meeting.

An end-to-end model of a Teflon-fed Pulsed Plasma Thruster called the PPT-4 that is being studied at the University of Illinois (see Section 9), has been developed. The model includes plasma generation, Teflon ablation, nozzle expansion, and plume expansion. The plume expansion is modeled using a particle approach. Momentum exchange and charge exchange collisions are included. Good agreement is obtained with measurements taken at the University of Illinois for plasma properties in the plume. It is found that the dynamics of the ions and the neutrals in the plume expansion are significantly different and this has an impact on contamination issues. A full description of the models and results is provided in ref. [4].

3 Massachusetts Institute of Technology

Current research topics at MIT include Hall thrusters and plumes, colloidal thrusters, arcjets, and tethers.

In scaling down high-power Hall thrusters, the MIT group developed a miniature 50-W thruster[5]. The thruster was tested under vacuum, demonstrating

[1] This Program has recently moved to the University of Michigan with its principal investigator, I.D. Boyd.

satisfactory performance. Detailed performance and thrust measurements are planned to verify figures predicted by the scaling model.

To analyze low-frequency (33 kHz) axial oscillation instabilities observed during SPT operation, a 1-D first order linear perturbation model was formulated[6]. The first solutions were determined by scanning the complex frequency plane. Two behavior patterns were noted. The first mode group had waves which translated through the thruster, with a fundamental harmonic of 49.7 kHz. The second group (74.2 kHz) exhibited sloshing behavior resembling a predator-prey cycle. Although all modes were found to be highly damped, it seems that an ionization-acoustic resonance instability could be excited. A 50-W Thruster with Anode Layer (TAL) type Hall thruster is being modeled. Because a TAL has conducting acceleration chamber walls, discharge characteristics differ from those of an SPT. A full Particle-In-Cell and Direct Simulation Monte Carlo (DSMC) methodologies have been adopted. Particles are followed individually, while ionization, scattering, charge exchange, are simulated with DSMC methods. The model predicts the electron energy distribution. A non-uniform grid is assumed. Another PIC model has also been developed[7]. It uses uniform gridding to simulate acceleration channels of Hall thruster-like geometries with both conducting and non-conducting walls. This model did not simulate an actual Hall thruster, but introduced some applicable computer models.

The 3-D Plume model developed previously by Oh[8] has been extended. The PIC/DSMC code models a plume expanding under vacuum and interacting with a spacecraft. Charge exchange, momentum exchange, and surface erosion are included.

Colloidal thrusters seem attractive for micropropulsion missions. They do not rely on gas-phase ionization and avoid lifetime limitations encountered in small scale Hall or ion thrusters. Miniscule thrust levels of individual colloidal needles may aid high-precision spacecraft control. Physics of these devices will be studied with Busek Company and Yale University through analytical/numerical modeling and experimentation. This will aid in designing a multi-needle high performance colloidal system.

The modeling of cesium seeded arcjets continues. In conventional arcjets, the largest efficiency loss is the energy required to dissociate and ionize propellant. Modeling predicts seeding with cesium reduces this loss to $< 1\%$, when the cesium is ionized and the hydrogen is molecular. Recently an improved model was validated on a finer grid, and the performance was examined while varying operating parameters like mass flow rate and applied power.

Electron current collection by positively charged bare tethers is being modeled with a PIC code[9]. Current in a tether traveling across the geomagnetic field generates electromotive force, providing propellant-less propulsion. Solar array charged batteries may supply the current. Conversely, current collection by tethers from ambient plasma can create drag or recharge batteries. Research focuses on bare tether current collection. Recent development includes unmagnetized PIC code. Local quasineutrality was imposed, and the simulation produced good quantitative results.

4 Ohio State University[2]

The Ohio State program comprises theoretical and experimental studies aimed at understanding and improving pulsed plasma microthruster (PPT) behavior. Recent modeling of PPT operation using the MACH2 magnetohydrodynamics code, guided by analytical solutions, has identified and quantified the mechanisms that cause inefficient propellant utilization. Briefly, for the usual conditions of PPT operation, the surface temperature of the propellant needed to support the discharge results in decomposition of much more propellant mass than is used during the discharge pulse. This extra mass accounts for the major portion of the total mass loss and leaves the thruster as post-pulse evaporation and macroparticle production. These processes contribute minimally to the thrust because the speed of the expelled mass depends on the temperature of the solid ($\ll 1000$ °K).

Higher magnetic fields (peak current per width or circumference) at the propellant surface provide substantial improvements in propellant utilization because more mass is used during the discharge pulse. The design of the electrical circuit parameters must, however, include the temporal-variation of the current, so that there is sufficient time for the ablation wave to merge with the depth of propellant decomposition. Simply delivering a high current pulse to narrow electrodes for a short time may not be sufficient to achieve this two-part optimization condition. Empirical exploration of PPT performance can readily miss the conditions for efficient behavior. Furthermore, the selection of propellant influences the

[2]Support from NASA Glenn Research Center, the Air Force Office of Scientific Research, and the Ohio Supercomputer Center.

matching of current and geometry by providing different values for decomposition temperature, thermal diffusivity and equilibrium vapor pressure (vs surface temperature). Recently, idealized representations have been used in order to survey candidate propellants. This work then connects to studies of deep-space trajectories involving in-situ propellant utilization. In particular, comet and asteroid rendezvous techniques offer opportunities for enhanced extra-solar exploration.

Modeling suggests that sufficiently long pulse times will assure all the available decomposed mass participates in the electromagnetic acceleration process. Microspacecraft, however, have limited available energy per pulse and will not permit these times with conventional circuits. Use of inductive energy storage can provide discharge durations of 10 to 50 microseconds at initial capacitor energies in the range of 50 J or less. An inductive energy-storage circuitry that uses the PPT plasma as the crowbar switch has been developed. This switch shorts the energy storage capacitor soon after the maximum energy has been delivered to an inductor in series with the PPT. As expected, such inductive storage and plasma switching prevents significant voltage reversal on the capacitor and improves PPT performance.

Activities to quantify the optical output of the PPT, in order to assess potential interference with sensors on near term missions (e.g., DS-3), extend to quantitative spectroscopy of the PPT plasma. Such spectroscopy allows detailed comparison with the modeling of the Teflon equation-of-state, but requires coaxial versions of the PPT. Annular and direct-pinch arrangements have been explored using MACH2 and the results showed higher propellant temperatures and poor propellant utilization. Consequently an inverse-pinch system was designed, for which MACH2 predicts substantially lower propellant temperature and greatly improved propellant use.

More details can be found in references [10]-[14].

5 Pennsylvania State University

An experimental investigation of a microwave resonant cavity thruster has been conducted with the objective of characterizing the engines performance. A 7.5 GHz engine operating with less than 100 W of input power has been tested under vacuum conditions in order to simulate the engines behavior in realistic space conditions. Various propellants have been used, including helium (see Fig. (2)), nitrogen and ammonia over a wide range of specific powers. Stable plasmas could be achieved at pressure levels up to 55 psia for helium and nitrogen propellants, and up to 7 psia using ammonia propellant. Mean chamber temperatures have been measured for all three propellants, yielding values as high as 1800 °K for helium and 2100 °K for nitrogen. As expected, the inlet temperature for ammonia propellant is relatively low, around 1250 °K, since some of the microwave power absorbed by the ammonia gas goes into various energy storage modes such as vibrational or rotational modes instead of raising the propellant temperature. Electron temperature measurements have been made by analyzing the spectrum of the light emitted by the 7.5 GHz thruster during atmospheric helium firings at four different wavelengths.

Figure 1: 7.5 GHz thruster operating with helium. (Penn State)

Electron temperature values were calculated employing the relative line intensity technique, and the commonly-made assumption of Local Thermodynamic Equilibrium (LTE) was examined at various pressure levels. It has been shown that the electron temperature would converge towards a single value around 4000 °K as the pressure would reach approximately 50 psia. This value is lower than those produced during previous investigations using much higher input power levels (>800 W). Doppler shift measurements of the light emitted by the exhaust plume in vacuum have been performed in order to evaluate the ejection velocity of the gas in the exit plane of a 52:1 area ratio nozzle. High spectral resolution measurements were made possible by the

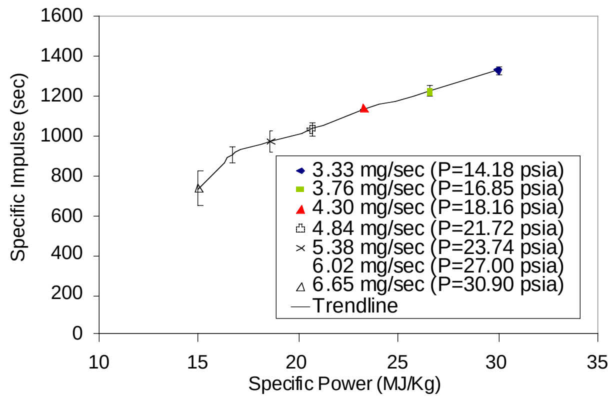

Figure 2: Centerline specific impulse vs. specific power for helium propellant. (Penn State)

use of a Fabry-Perot interferometer combined with a spectrometer. Two high-transmittance fiber optic cables were used in order to simultaneously collect the light from different angular positions and carry the signal through the vacuum tank. The Doppler shift was measured using the helium emission line located at 5876 Angstroms. Centerline specific impulses have been measured for specific powers ranging from 15 MJ/Kg up to 30 MJ/Kg (see Fig. (2)). Values as high as 1330 s have been recorded. In order to obtain thrust and specific impulse data using other propellants without the effect of buoyancy forces, a vertical mechanical thrust stand has been built. A Linear Voltage Displacement Transducer (LVDT) has been integrated into the design, enabling a thrust resolution as high as 0.5 mN.

6 Princeton Plasma Physics Laboratory

The conditions for steady plasma acceleration from subsonic to supersonic velocities in the Hall thruster were investigated[15]. The dynamics can be usefully posed in a general way. A force opposing the flow is exerted on the plasma in the Hall thruster in the subsonic regime (a drag due to ionization), and a force supporting the flow is exerted in the supersonic regime (the force due to the magnetic field pressure). As in a Laval nozzle, a smooth steady acceleration with the sonic transition inside the channel occurs under certain conditions only. Such acceleration is seen at the separatrix in the phase space plot shown in Fig. (3). If those conditions are not satisfied the flow is expected to be intermittent and perhaps unstable.

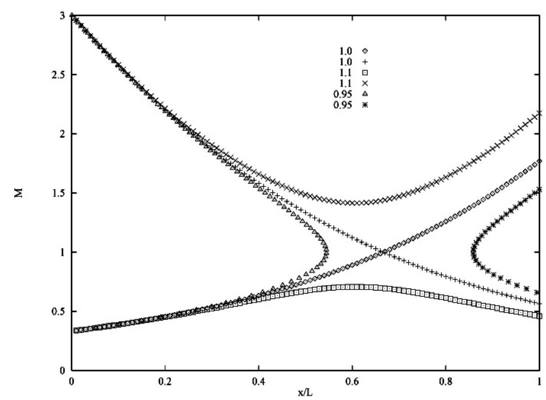

Figure 3: Sonic transition in Hall thruster. (PPPL)

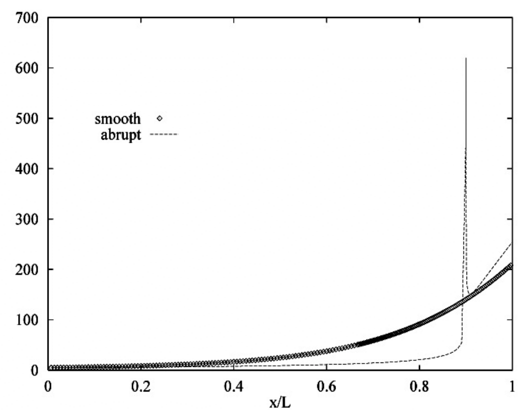

Figure 4: Sonic transition in Hall thruster with segmented cathode. (PPPL)

By introducing a discontinuity at the channel wall, it is shown theoretically how to control of the location of the sonic transition. For example, the addition of a segmented electrode enlarges the domain of parameters where a steady acceleration to supersonic velocities is possible. The electric potential profile is then controllable. A large localized electric field is generated at the exit as shown in Fig. (4), so that the thruster can be operated optimally.

A novel Hall thruster concept is also being developed at PPPL, based on segmented cathodes[15]. The segmented cathode Hall-current thruster provides electrons through emissive cathodes along the thruster channel, separated by dielectric insulators, with segments held at different potentials through separate power supplies. In principle, the efficiency of such thrusters can approach the theoretical maximum. The segmented cathode approach provides an acceleration region that is localized as much as possible. The localization can be in a region of concave magnetic field for maximum focusing, resulting in less plume divergence.

A laboratory model segmented cathode Hall thruster model was designed and built at PPPL[16]; very preliminary measurements show that it can operate as a state-of-the-art thruster with efficiencies in the range of 50%. The thruster is being tested on the recently built PPPL thruster facility. The PPPL vacuum system consists of a stainless steel vacuum vessel, with diameter 2.29 m and 8.38 m long. It is equipped with a 32 inch diffusion pump, backed by a two stage roots-pump system, capable of a pumping speed better than 50,000 l/s. Under Xenon mass flow of 23 sccm, the vacuum system maintained a back pressure of 2.4×10^{-6} Torr, corresponding to better than 12,100 l/s Xenon pumping speed.

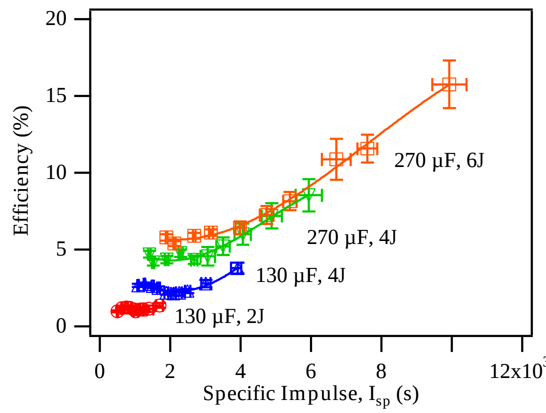

Figure 5: Measured efficiency as a function of specific impulse for PT5 using argon propellant showing variation in performance due to different capacitance values and initial stored energy levels. (Princeton-EPPDyL)

7 Princeton University's EPPDyL

Gas-Fed Pulsed Plasma Thruster Research. Previous collaborative work between Science Research Lab. Inc. and the Electric Propulsion and Plasma Dynamics Lab. (EPPDyL)[17] led to the implementatiion of a high repetition rate (5 kHz) pulsing scheme that groups thruster discharges into a *burst* with effective propellant utilization fractions well exceeding 90% with standard (1 ms) gas-valves. Due to their scalable performance, clean exhaust, light-weight, low-inductance capacitor bank, modern GFPPTs are well suited for a variety of small spacecraft applications. Until recently, however, a reliable database of measured GFPPT performance has not been available to mission planners.

Previous performance measurements at EPPDyL [17, 18] and early experiments at Fairchild Republic[19] have been shown to be significantly influenced by pump oil contamination at low mass bits. Substantial efforts have been made at EPPDyL to eliminate this problem including the implementation of liquid-nitrogen cooled baffles and developing a protocol for thruster decontamination. Recent impulse measurements taken with the same thruster in a cryo-pumped facility at NASA-JPL agreed with data taken at EPPDyL under the new performance measurement protocol clearing the way for a new database which was used to check on predicted GF-PPT scaling and clarify the nature of the acceleration mechanism. Previous measurements showed [20] that asymmetric discharge initiation reduced thruster performance. This problem has been corrected with a new discharge initiation circuit that distributes the energy to each spark-plug evenly and insures a repeatable symmetric discharge initiation. The database shown in Fig. (5), covers a range of low energy per pulse levels, discharge capacitance and mass bits. The data set was found[21] to agree well with an analytical model of *electromagnetic* current sheet acceleration with the efficiency and thrust-to-power ratio proportional to the square root of the discharge capacitance. The results have clarified the new research directions that are presently being pursued with AFOSR support to further improve the performance. These include: 1) Increasing the capacitance while keeping the mass of the capacitors low, 2) Increasing the inductance per unit length (using permanent magnets and/or plane electrodes) 3) Improving uniformity of discharge initiation (using pulsed e-beam or optical sparking techniques) and 4) Reducing the canting of the current sheet.

The problem of current sheet canting is of a fundamental question that has direct impact on reducing performance as it leads to non-axial velocity vec-

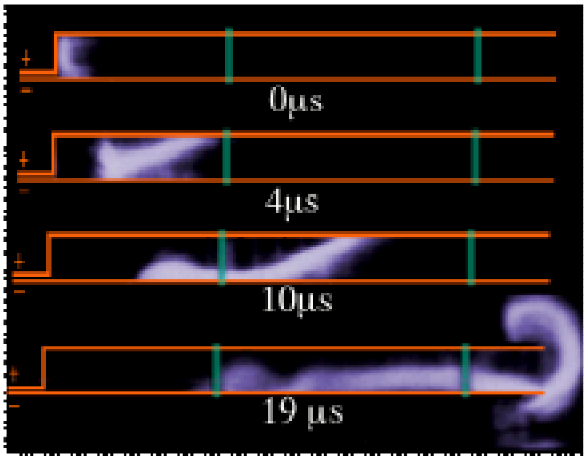

Figure 6: Evolution of plasma sheet in a parallel plate pulsed accelerator imaged with an Imacon camera through an argon ion filter at 500,000 fps showing the development of structure and canting. (50 kA flat-top 25 μs current pulse in argon at 100 mTorr). (Princeton-EPPDyL)

tors and a reduction of the total change of inductance during the pulse. Consequently, a large parallel plate GF-PPT with wide optical access has been constructed and will be the focus of detailed study with optical diagnostics. Imaging of the plasma using an argon ion filtered Imacon camera capable of recording at a rate of 20 million frames per second has revealed the complex evolution of the plasma sheet which develops definite structures and quickly cants with respect to the thruster axis as shown in Fig. (6).

Other ongoing projects at EPPDyl include experimental and numerical studies (under NASA-JPL support) of steady-state lithium Lorentz Force accelerators (MPDT) intended for high power ($\simeq$500 kW) interplanetary propulsion (to be presented at the IEPC), the development of a mega-pixel microthruster chip in collaboration with Honeywell and investigations of radiative and e-beam energy addition to supersonic flows for high specific impulse thermal propulsion[22].

8 Stanford University

The research at Stanford focuses primarily on the study of inert-gas plasma thrusters, including Hall thrusters and inert gas arcjets. In addition to the study of these plasma electric thrusters, the researchers at Stanford have initiated development of cluster-beam (colloid) electric propulsion technology.

The main objective of their Hall thruster activities is to develop a fundamental understanding of electron transport mechanisms in these plasma discharges. A detailed understanding of electron transport can lead to improved, compact, and/or more efficient thruster designs. In most co-axial Hall thrusters, the ionization peaks in the vicinity of the peak magnetic field, and, there is a residual field upstream of the ionization zone. Electrons generated by the cathode or produced in the ionization zone must traverse this field without the opportunity to undergo momentum-transfer collisions. Because of the relatively low gas density in the discharge channel, the electrons rely on wall collisions and/or fluctuations to enhance the cross-field electron transport. The limited transport in this region of the plasma channel leads to ohmic dissipation and acceleration losses, limiting engine performance. Using advanced laser diagnostics, optical and electrostatic probe characterization, the Stanford researchers have found that this region upstream of the ionization zone is rich in oscillatory phenomenon, including fluctuations in the plasma density and electron energy, all of which seem to lead to an overall anomalous increase in the electron conductivity. An example of a frequency-position rendering of fluctuations in the optical emission intensity of a neutral xenon line is shown in Fig. (7). We see that while there is intense fluctuations in the plasma in regions close to the exit plane Recent experiments indicate that the axial conductivity is some 10 to 100 times greater than that determined by classical arguments, and they have focused on further increasing the conductivity by actuating these fluctuations using external means.

The findings suggesting enhanced (anomalous) transport led to the conjecture that a Hall thruster with open electron-drift, i.e., with a terminated linear geometry rather than a closed co-axial geometry, should function because of the unusually high ratio of axial to Hall current. During the past year, the Stanford researchers have designed and fabricated a linear Hall thruster, and have operated in the 50-100 W ultra-low power range. A photograph of this thruster firing in is shown in Fig. (8). The successful operation of this thruster, depicting a very characteristic I-V behavior typical of Hall discharges, is an indicator of the unnecessary requirement to close the Hall current. The linear geometry device has been operated with different wall materials. It is found

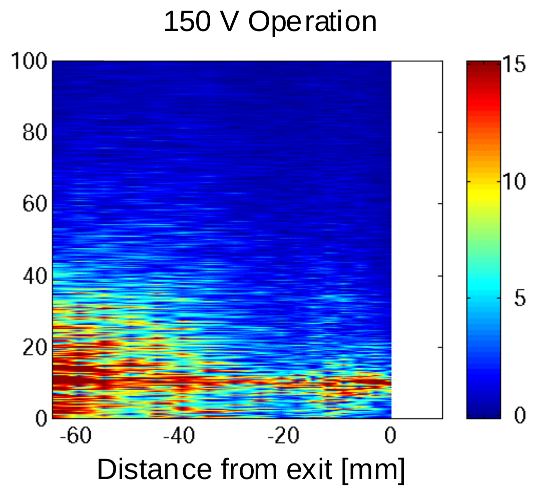

Figure 7: Frequency-position rendering of fluctuation in plasma emission from electronically excited neutral xenon. Note intense fluctuation near the anode located at a position of $z = 75$ mm. (Stanford)

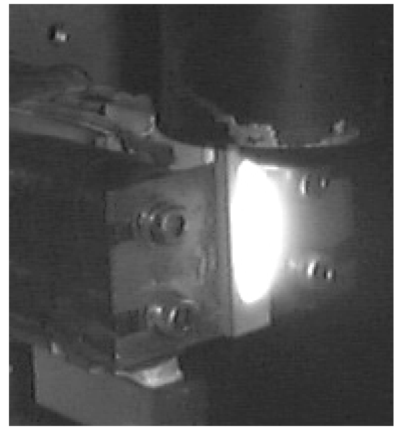

Figure 8: Photograph of a linear geometry Hall thruster with an open electron drift operating at 50-100 W. (Stanford)

that the composition of the insulating channel wall greatly influences the axial current flow. This is an indirect indicator of the importance of wall effects on the axial electron transport, and ongoing experiments with this convenient geometry are aimed at studying the influence of many different wall materials on axial electron transport. Efforts are also underway to scale the device power to 5-10 W, which would be attractive to applications such as microsatellite propulsion.

9 University of Illinois at Urbana-Champaign

Investigations at the University of Illinois include studies of two types of coaxial thrusters and pulse circuit development. The PPT-4 thruster[23] shown in Fig. (9) is predominantly gasdynamic, and generates nearly double the thrust of rectangular geometries (29 μN-s/J) at an I_{sp} of 755 s. Propellant feed is from the side into a small-diameter cavity. Current flows axially from the anode at the back of the cavity into a dielectric nozzle with annular cathode. Magnetic probe measurements show that the current flow is predominantly axisymmetric, but is slightly biased toward the side-mounted igniter plug (see figure). Electrostatic probe measurements of n_e and T_e show a high degree of axisymmetry, densities of $\simeq 2 \times 10^{14}$ cm^{-3} and a typical electron temperature of 1.5 eV. It is concluded that the thrust vector is nearly axial, and that benefit is derived from the nozzle.

Figure 9: Gasdynamic PPT. (UIUC)

The second type of PPT is a coaxial electromagnetic type, PPT-5[24] shown in Fig. (10). The external circuit of this thruster includes a 20 J capacitor, an inductor, and a diode assembly that permits unidirectional current flow out of the capacitor and parallel to the discharge. The igniter plug is mounted on-axis to provide a high degree of discharge symmetry. The circuit is operated in a low-impedance mode to maximize the discharge current integral $\int I^2\, dt$ and hence impulse bit. Investigations have been performed on propellant geometry to achieve high specific impulse

Figure 10: Electromagnetic PPT. (UIUC)

(1000-5000 s) to raise efficiency. Both Teflon and high-density polyethylene have been tested, with significantly higher I_{sp} achieved with the polyethylene. Thermocouple measurements have been used to measure heating of the capacitor and thruster head.

Investigations are also being performed on PPT circuits in the 5 J range to eliminate the igniter plug. A silicon controlled rectifier (SCR) is employed to switch the high voltage capacitor to the thruster electrodes, causing breakdown. Issues include preventing SCR failure due to the high currents and current rise-rates, and achieving sufficient voltage to cause breakdown across a few-cm gap.

10 University of Michigan (PEPL)

The Plasmadynamics and Electric Propulsion Laboratory (PEPL) is involved in Hall thruster research sponsored by the Air Force Office of Scientific Research (AFOSR), and ion thruster and hollow cathode research sponsored by NASA. The Jet Propulsion Laboratory (JPL), the Ballistic Missile Defense Organization (BMDO), and the AFOSR sponsor Field Emitter Array Cathode (FEAC) research.

AFOSR-sponsored projects include 1) Characterization the 5 kW P5 laboratory-model Hall Thruster plume and interior with probes, mass spectroscopy, microwave and optical diagnostics; 2) Development of a high-speed reciprocating probe system with a residence time of 100 milliseconds for internal thruster characterization 3) Testing of propellant-less Field Emitter Array Cathodes (FEACs) for small EP thrusters and develop a lifetime and field emission model for FEACs (JPL/BMDO sponsorship as well)

Energy distribution data collected 10 cm from the exit plane and 15 degrees off-axis of the P5 Hall thruster at 300 V-5.3 A and 58 sccm showed numerous xenon-neutral charge exchange collisions as illustrated in Fig. (11). There data show a primary peak at 263 V, which corresponds to the most probable ion acceleration voltage as well as high- and low-energy "tails" to this peak, which correspond to elastic collisions between ionic species within the plume. There are also distinct peaks at multiples of the primary peak voltage that correspond to charge exchange collisions. This indicates the presence of single, double, triply, and quadruply charged xenon ions within the plume of the thruster.

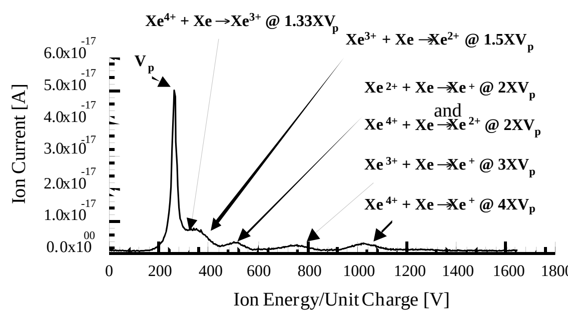

Figure 11: Energy distribution data collected 10 cm from the exit plane and 15 degrees off-axis of the P5 Hall thruster. (UM-PEPL)

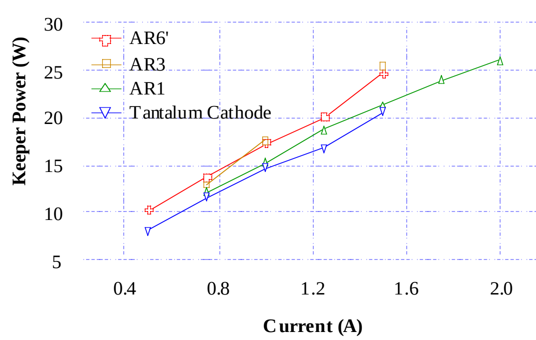

Figure 12: This figure shows the 20% reduction in power consumption for the 2nd generation (Tantalum) lab-model cathode designed at PEPL. (UM-PEPL)

Electron temperature data were obtained using a triple electrostatic probe and the PEPL High-speed Axial Reciprocating Probe (HARP) system. The HARP system operates at speeds in excess of 250 cm/s and accelerations over 7 g's. It is capable of inserting and removing the triple probe on time scales under 100 ms, minimizing perturbations to the local plasma and to thruster operation. 2-D mapping of electron temperature inside the discharge chamber of the P5, operating at 300 V and 5.3 A revealed a temperature profile that agrees well with previously published results on similar thrusters.

NASA sponsored projects include: 1) Development of a comprehensive thermal model of ion thrusters, including self-heating terms 2) Development of low-power, low-propellant consumption hollow cathodes 3) Development a two-stage Hall thruster 4) Development a laser-based erosion measurement system for ion thrusters

A 30-cm Functional Model Thruster (FMT), built at the NASA Glenn Research Center, was modified to provide optical access to the region surrounding the discharge cathode, and exhibited performance characteristics similar to the flight engine.

Langmuir probe data were obtained inside a 3.2-mm-diameter, first-generation cathode and showed sharp gradient in electron number density in the vicinity of the cathode orifice. Fig. (12) compares 1st and 2nd generation hollow cathode performance and shows a 20% reduction in power consumption for the 2nd generation laboratory-model cathode which is made entirely of tantalum to reduce by a factor of two the thermal conductivity. The insert inner diameter has been nearly doubled, thereby increasing the electron impact ionization rate for a given neutral density and thermionic emission current density. The orifice plate geometry has also been improved to facilitate ion transport by reducing the cathode sheath area along the chamfered orifice wall.

11 University of Southern California

The interaction of spacecraft thruster plumes with a spacecraft and the ambient low-Earth orbit (LEO) environment is of interest to spacecraft mission planners for a wide variety of reasons. Although spacecraft propulsion systems are mission enabling, they can also be sources for particulate, molecular and radiation contamination on and near spacecraft surfaces. In early 1995, the need for a national facility capable of performing meaningful LEO plume and contamination studies was identified by researchers at the University of Southern California and the Air Force Research Laboratory. One motivation was the present lack of a facility that could be used for ground-based studies of the many thruster interaction phenomena associated with the LEO high speed, rarefied flow environment. A second objective was to provide a facility that would be able to faithfully simulate the low pressures experienced by thrusters in space during operation. A matter of significance, particularly for electric thrusters such as the Hall effect devices that operate based on a discharge directly exposed to the space environment. The same objectives are also of vital importance for meaningful contamination studies. Interest in realistic simulation of the space environment as applied to the study of spacecraft contamination and thruster plumes has led to the development of the David P. Weaver Collaborative High Altitude Flow Facilitys (CHAFF) Chamber-IV[25].

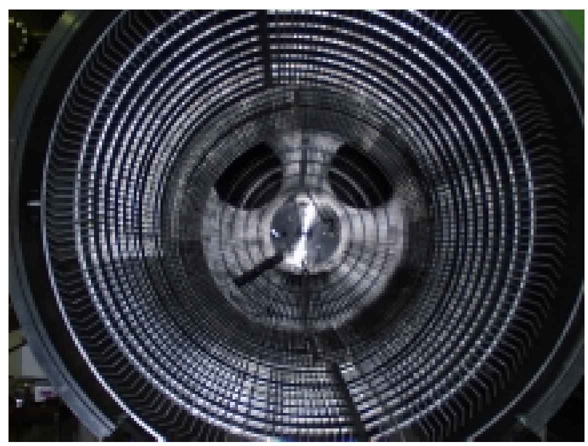

Figure 13: Cryogenic pumping fin array of the CHAFF-IV plume and contamination facility. (USC)

The outer envelope of CHAFF-IV is a stainless steel vacuum chamber measuring 3 m in diameter and 6 m in length. In addition to a rather substantial CHAFF-IV uses a multi-fin cryogenically cooled array (20 °K) that completely covers the interior of the chamber providing an available condensing surface area of 590 m^2 as shown in Fig. (13). The geometry of the pumping array capitalizes on the fact that both neutral and ion species from spacecraft propulsion systems predominantly undergo diffuse reflections when impacting at angles normal to the surfaces they encounter. Preliminary figures of merit for the equivalent altitude possible for various propulsion systems vary between 150-350 km (depending on thruster type and mass flow). The effective pumping speed is predicted to be between 9×10^6 and 3×10^7 liters/sec, and the facility is expected to accommodate thruster power levels up to 3500 W without the addition of liquid helium.

12 Worcester Polytechnic Institute (WPI)

Particle/Fluid Modeling of Pulsed Plasma Thruster Plumes[26]. Integration of Pulsed Plasma Thruster (PPT) onboard spacecraft requires the evaluation of potential plume/spacecraft interactions. Characteristics of PPT plumes were reviewed and the issues related to the modeling of the unsteady, partially ionized, collisional plasma were considered. An axisymmetric, hybrid particle-fluid model was developed. Neutrals and ions are modeled with a combination of the Direct Simulation Monte Carlo (DSMC) and a Hybrid-Particle-in-Cell (hybrid-PIC) method. Electrons are modeled as a massless fluid with a momentum equation that includes collisional contributions from ions and neutrals. The code incorporates a dual-grid structure, sub-cycling for the time integration, and time-varying particle injection. The Non-Time-Counter methodology is used for neutral-neutral, elastic ion-neutral, and charge exchange collisions. Ion-electron collisions are modeled with the use of a collision force field. Electric fields are obtained from a charge conservation equation under the assumption of quasi-neutrality. Simulations are performed using PPT conditions representative of a NASA-Glenn PPT operating at discharge energies of 5, 20 and 40 J. The results demonstrate the expansion of the neutral and ion components of the plasmoid during a pulse, the generation of low-energy ions and high-energy neutrals due to charge exchange reactions, and the generation of neutral and ion backflow. Numerical predictions were compared with unsteady plume electron density data and show good quantitative agreement. Backflow predictions were made for the three discharge energy levels considered.

Analysis Of Triple Langmuir Probe Measurements In The Plume Of A Pulsed Plasma Thruster[27]. An experimental apparatus using triple Langmuir probes was designed to obtain electron temperature and density in the plume of a NASA-Glenn laboratory model pulsed plasma thruster. Electron temperature and density were obtained on two planes parallel and perpendicular to the thruster electrodes passing through the thrusters centerline. Measurements were obtained for various radial distances and polar angles and discharge energy levels. Plume properties showed large angular variation on the perpendicular to the electrodes plane but small variation on the parallel plane confirming the asymmetry of the PPT plume. Electron density and temperature were found to decrease with increasing radial distance from the Teflon surface. More details on these experiments and results can be found in ref. [27].

Analysis Of Triple Langmuir Probe Measurements In The Near-Exit Region Of A Gas-Fed Pulsed Plasma Thruster[28]. Triple Langmuir probes were used to measure electron number density, and electron temperature in the near-exit region of a laboratory model gas-fed pulsed plasma thruster. Triple Langmuir probe data were obtained on a plane parallel to the thruster electrodes at radial distances of 3 and 7 cm downstream of the propellant inlet and angular positions of 0, 10, 20, and 30 degrees. The thruster was operated with Xe propellant, 2 J per pulse, and a mass flow rate of 3 mg/s. Analysis shows that average density at the thruster exit plane is in the range of 5×10^{18} to 2.5×10^{19} m^{-3} and temperature is in the range of 0.5 to 4 eV. At a radial distance of 4 cm downstream from the exit, the density is in the range of 2×10^{18} to 1×10^{19} $m^{-3}$and temperature in the range of 0.2 to 1.4 eV. Temperature averaged over the duration of a pulse is in the range of 0.4 to 1.3 eV and shows angular and radial variation.

Acknowledgements The author wishes to thank the various principal investigators at the above institutions for their contributions.

References

[1] D. Burtner and P.J. Wilbur. Plasma contacting with a solid expellant. In 37^{th} *Aerospace Sciences Meeting and Exhibit*, 1999. AIAA-99-0381.

[2] M.W. Crofton and I.D. Boyd. Analysis of selected performance results for several flight-model ion engine grids. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2443.

[3] D.B. VanGilder, M. Keidar, and I.D. Boyd. Physical modeling in particle simulations of hall thruster plumes. In 35th *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2294.

[4] I.D. Boyd, M. Keida, and W. McKeon. Pulsed plasma thruster modeling from plasma generation to plume far-field. In 35th *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2300.

[5] V. Khayms and M. Martinez-Sanchez. Design of a miniaturized Hall thruster for microsatellites. In 32nd *Joint Propulsion Conference*, Lake Buena Vista, FL, USA, 1996. AIAA-96-3291.

[6] R.A. Noguchi. Linear 1-D Analysis of Oscillation Instabilities in Stationary Plasma Thrusters. Master's thesis, MIT, Department of Aeronautics and Astronautics, Cambridge, MA, USA, 1999.

[7] P. Beidler. Two Dimensional Particle-In-Cell Simulation Model for Hall Type Thrusters. Master's thesis, MIT, Department of Aeronautics and Astronautics, Cambridge, MA, USA, 1999.

[8] D. Oh. *Computational Modeling of Expanding Plasma Plumes in Space Using a PIC-DSMC Algorithm*. PhD thesis, MIT, Department of Aeronautics and Astronautics, Cambridge, MA, USA, 1997.

[9] T. Onishi. Electron Current Collection by a Positively Charged Tether Using a Particle-In-Cell Method. Master's thesis, MIT, Department of Aeronautics and Astronautics, Cambridge, MA, USA, 1998.

[10] R.L. Burton and P.J. Turchi. Pulsed plasma thruster. *Journal of Propulsion and Power*, 14(5):716–735, 1998.

[11] P.J. Turchi, R.J. Leiweke, and H. Kamhawi. Design of an inductively-driven pulsed plasma thruster. In 32nd *Joint Propulsion Conference*, Lake Buena Vista, FL, USA, 1996. AIAA-96-2731.

[12] P.J. Turchi. Directions for improving PPT performance. In 25th *International Electric Propulsion Conference*, Cleveland, OH, USA, 1997. IEPC-97-038.

[13] C.S. Schmahl and P.J. Turchi. Development of equation-of-state and transport properties for molecular plasmas in pulsed plasma thrusters. In 25th *International Electric Propulsion Conference*, Cleveland, OH, USA, 1997. IEPC-97-124.

[14] P.J. Turchi. Theoretical investigation of pulsed plasma thrusters. In 34th *Joint Propulsion Conference*, Cleveland, OH, USA, 1998. AIAA-98-3807.

[15] A. Fruchtman and N.J. Fisch. Novel configuration for the hall thruster. In 35th *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2142.

[16] N.J. Fisch, Y. Raitse, A. Litvak, and L. Dorf. Design and operation of hall thruster with segmented electrodes. In 35th *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2572.

[17] J.K. Ziemer, E.A. Cubbin, E.Y. Choueiri, and D. Birx. Performance characterization of a high efficiency gas-fed pulsed plasma thruster. In 33rd *Joint Propulsion Conference*, Seattle, Washington, July 6-9 1997. AIAA 97-2925.

[18] J.K. Ziemer, E.Y. Choueiri, and D. Birx. Trends in performance improvements of a gas-fed pulsed plasma thruster. In 25th *International Electric Propulsion Conference*, Cleveland, Ohio, August 24-28 1997. IEPC 97-040.

[19] W.J. Guman and W. Truglio. Surface effects in a pulsed plasma accelerator. *AIAA Journal*, 2(7):1342–1343, July 1964.

[20] J.K. Ziemer, T.E. Markusic, E.Y. Choueiri, and D. Birx. Effects of ignition on discharge symmetry in gas-fed pulsed plasma thrusters. In 34th *Joint Propulsion Conference*, Cleveland, Ohio, July 13-15 1998. AIAA 98-3803.

[21] J.K. Ziemer, E.Y. Choueiri, and D. Birx. Is the gas-fed ppt an electromagnetic accelerator?: An investigation using measured performance. In 35th *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2289.

[22] V.P. Chiravalle, R.B. Miles, and E.Y. Choueiri. Laser propulsion using a molecular absorber. In *34th AIAA Joint Propulsion Conference*, Cleveland, OH, 1998. AIAA-98-3932.

[23] R.L. Burton and S.S. Bushman. Probe measurements in a coaxial gasdynamic PPT. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2288.

[24] E. Antonsen, R.L. Burton, and F. Rysanek. Studies of energy losses in a coaxial electromagnetic pulsed plasma thruster. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2292.

[25] F. Lutfy, A. Green, E.P. Muntz, and A. Ketsdever. Investigation of the operational envelope of the CHAFF-IV Plume and Contamination Facility. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2719.

[26] N.A. Gatsonis and Y. Xuemin. Particle/fluid modeling of pulsed plasma thruster plumes. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2299.

[27] R. Eckman, L. Byrne, E. Cameron, N.A. Gatsonis, and E. Pencil. Analysis of triple langmuir probe measurements in the plume of a pulsed plasma thruster. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2286.

[28] M. Gagne, N.A. Gatsonis, J. Blandino, Ziemer J., and E.Y. Choueiri. Analysis of triple langmuir probe measurements in the plume of a pulsed plasma thruster. In 35^{th} *Joint Propulsion Conference*, Los Angeles, CA, USA, 1999. AIAA-99-2286.