Overview of Electric Propulsion Research in U.S. Academia

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Abstract

An overview is presented of electric propulsion research carried out in U.S. academic institutions. Universities in the U.S. are engaged in a wide range of research, varying from fundamental studies in micro thruster concepts, to future flight involving magneto plasma sails.

I. INTRODUCTION

Fundamental and applied research on electric propulsion in United States Academic Institutions span across several disciplinary and topical areas ranging from fundamental studies of the molecular-scale mechanisms how electric propulsion plasmas are accelerated, to how electric propulsion plumes will impact the operational characteristics of large satellite structures. At the last International Electric Propulsion Conference held in Toulouse, France (Spring 2003), there were approximately fifteen U.S. academic institutions represented. While some of the experimental programs make use of national research ground-test facilities made available by both NASA and the U.S. Air Force, many, if not most of the Institutions have state-of-the-art facilities to carry out both applied and fundamental research relevant to the U.S. interest in future space propulsion applications.

In this paper, we present a sampling of these activities. The paper and its accompanying presentation is not intended to be a complete treatise on this subject, as contributions have not been received from all U.S. Academic Institutions, and apologies are extended for inadvertent omissions due to the background research carried out by one of the authors (MC). The paper does attempt to illustrate the richness and diversity of the research, despite these possible omissions.

II. PROGRAM HIGHLIGHTS

A. Research at Worcester Polytechnic Institute

Research at the Worcester Polytechnic Institute (WPI) falls under the programs headed by Professors John Blandino and Nikolaos Gatsonis. Blandino's research is largely focused on the study of colloid thrusters for small satellite propulsion, and in the development of novel, earth-orbiting spacecraft formations. The investigation of colloid thruster technology is a continuing activity with a recent focus on the mapping of the plasma potential of a thruster operating with a carbon nanotube (CNT) cathode neutralizer [1]. This experimental activity is a collaborative effort with an industrial partner - BUSEK Co., which is developing this technology for demonstration on the NASA ST-7 Mission. Beyond demonstration on ST-7, the colloid thruster is also a candidate for the Laser Interferometer Space Antenna (LISA) Mission. The experiments are designed to investigate the beam and space-charge neutralization characteristics of the CNT cathode over a range of colloid source operating conditions. Any performance sensitivity resulting from the physical location of the cathode relative to the electrospray is also of interest. These data will be available for validation of numerical simulations of the droplet/ion/electron plasma, aid in the design of the next generation breadboard thruster, and provide further understanding needed to assess potential contamination risk to sensitive instruments and payloads.

A facility has been set up to perform flow rate measurements and two-phase flow visualization in microchannels. The rectangular microchannels are fabricated in silicon and have with characteristic lengths of tens to hundreds of microns. These two-phase flow studies have broad applicability in active cooling of microelectronics in addition to micropropulsion. Studies this past year [2] have focused on the Vaporizing Liquid Microthruster (VLM) developed by the Jet Propulsion Laboratory. In the VLM, the fluid (water or alcohol) is vaporized by an integral heater in a channel roughly 700 microns wide, 300 microns deep and 5 millimeters long. Visual observations are possible through a Pyrex cover glass over the channel. After vaporization, the fluid vapor is expanded through a micromachined nozzle to produce thrust. The goal of this work is to identify two-phase flow regimes in this microchannel under different operating conditions with the intent of improving thermal design and thruster efficiency.

Of particular interest is identifying and controlling the dry-out point along the heated channel which, if located too far from the nozzle exit, can lead to excessive heat dissipation in the silicon substrate resulting in poor efficiency. Recent work performed by students jointly with members of the Distributed Space Systems Group at the Goddard Space Flight Center involved the development of novel, earth-orbiting spacecraft formations. These formations were described analytically in terms of their classical orbital elements for future consideration by mission designers. In addition, the individual spacecraft orbits were propagated using STK and Matlab to investigate the performance over time of the formations when subject to J2 gravitational perturbations [3]. Other work in the area of mission design has continued to explore innovative applications of electric propulsion to enable or enhance science capabilities of formations of distributed spacecraft in earth orbit. Propulsion options including Hall, ion and PPT were evaluated for a geosynchronous formation of three spacecraft designed for deep space imaging [4].

Prof. Gatsonis' research is on the study of pulsed plasma thruster plumes, plume modeling, and micropropulsion modeling. Recent studies of plumes include measurements in the plume of a teflon pulsed plasma thruster. A directional microchannel plate Retarding Potential Analyzer (RPA) was designed and used to obtain preliminary ion energy distribution measurements in the high-density plume of a solid teflon PPT. The design addresses various sizing issues and transient phenomena inherent to the relatively high particle number densities, specifically electrode aperture parameters and wake flux. They have completed and tested a hybrid RPA design [5], consisting of a single orifice electrode series coupled with a microchannel plate having less than 1% transparency and a geometric acceptance angle of less than 0.6^{o}.

In another project, the WPI team has been developing an advanced hybrid (particle/fluid) computational PPT plume model in order to evaluate potential plume/spacecraft interactions. The code combines the Direct Simulation Monte Carlo (DSMC) and a Hybrid-Particle-in-Cell (hybrid-PIC) method. Electric fields are obtained from a current balance formulation. The effects of background on a pulsed plasma plume expansion are investigated in a recent paper [6]. Simulations are performed for vacuum-chamber, LEO and GEO plasma conditions.

The Gatsonis activity also includes modeling of plasma micropropulsion. This research addresses fundamental mathematical and computational issues in plasma micro-flows. The research aims in the modeling of electric microthrusters (e.g. ion, Hall, FEEP, resistojet) and associated devices (e.g. hollow cathodes, field emission arrays) in order to optimize basic performance characteristics. In addition the research aims in the modeling of electric micro thruster plumes in order to investigate potential plume/microspacecraft interactions. The code under development uses concepts of DSMC, PIC on unstructured grids with adaptation. As an application they consider the operation of field emission (FE) arrays that can be part of electric micropropulsion devices. Issues are addressed of numerical heating in PIC computations on unstructured 3-D grids [7]. Various alternatives of particle and force weighting schemes are considered. The problem of the collisionless sudden expansion of plasma into vacuum is investigated. Results are compared with analytical and previous computational work.

Particle methods are also used to model the basic problem of ion beam neutralization – i.e., the coupling of the electrons to an ion beam, such as from an electric propulsion device. Under investigation are the coupling mechanisms between the beam, neutralizer, and background plasma. Initial simulations of an ion beam in background plasma with neutralization have been carried out with a 3D unstructured DSMC/PIC code [8].

B. Research at Stanford University

Research at Stanford University includes the study of fundamental transport processes in Hall thrusters. In previous years, the emphasis was placed on collecting an extensive dataset on internal plasma properties that characterized the spatial-variation in the effective Hall parameter, $\omega\tau_{eff}$, the inverse of which is a measure of the crossed-field electron mobility. In the vicinity of the discharge channel exit, where there are intense fluctuations in the plasma properties, the Hall parameter departs from the classical value, and is found to be close to the Bohm value of $\omega\tau_{eff} \sim O(10)$. However, within the region of the strongest magnetic field, the results are also found to be dependent on the electron shear rate due to the azimuthal electron current. These results have led to the development of a simple model for the conductivity [9] where, in the region of the flow were the shear is strongest, the Hall parameter approaches $\omega\tau_{eff} \approx O\ (100)$. It is noteworthy that a Hall parameter of this magnitude requires an azimuthal current density that is 100 times the axial current density. More recent activities have focused on independent verification for this strong spatial variation in the azimuthal current density, including the use of distributed external antennas, which map out directly, the azimuthal current sources following the abrupt termination of the discharge current in the circuit, and extinction of the plasma [10]. New experiments using multiple distributed electrostatic probes [11] to map out the propagation characteristics of plasma fluctuations including the wavevector power spectra show strong turbulent energy cascades at smaller scales, with a reduction in the amplitude of fluctuations in regions where there is strong shear. In conjunction with probe-based studies, a streak camera has been used to image small-scale turbulent features that cannot be studied with the limited resolution of distributed Langmuir probes, in an attempt to better quantify the role that turbulence plays on electron transport.

Researchers at Stanford University are also studying the possible role that electron-wall interactions play on cross-field electron transport. Using a linear-geometry Hall thruster as a test-bed [12], they studied the effects of novel wall materials such as polycrystalline diamond (a material with a low secondary electron emission coefficient) on the Hall discharge behavior.

In collaboration with Prof. E. Fernandez at Eckerd College, the Stanford team is developing numerical simulations for Hall thrusters, including 2-D and 3-D models based on Hybrid Continuum/Particle-in-Cell descriptions [13]. The 2-D simulations make use of the transport models derived from experiments, as discussed above, while the 3-D version does not require semi-empirical models for turbulence-induced transport, since it captures the azimuthal propagation of plasma density and potential (field) fluctuations which give rise to enhanced axial electron flow. At present, these simulations include elementary treatments of the plasma-wall interactions. Boundary conditions under development include secondary emission due to the photoelectron effect associated with the strong vacuum ultraviolet emission generated by the resonance transitions in xenon. Future research at Stanford focuses on the development of new thruster geometry that will minimize/eliminate wall erosion, and two-stage Hall thrusters that operate on metal vapor such as cadmium and barium, for high-efficiency and high specific impulse applications.

C. Research at the University of Michigan

Research at the University of Michigan falls under the programs headed by Professors Alec Gallimore and Ian Boyd.

Professor Gallimore's group conducts research on a wide array of electric propulsion problems. Over the past few years, they have developed a high-speed reciprocating probe system (HARP), with a discharge chamber residence time <100 msec, to measure floating potential and very near-field ion current density in the NASA-173m Hall thruster. They have also used this HARP system to measure plasma density (Ne), electron temperature (Te), and plasma potential in a NSTAR derivative ion thruster discharge chamber and are currently modifying a NEXT-class (40 cm) ion thruster for HARP discharge chamber plasma measurements.

In related projects, they are using electrostatic energy analyzers (ESAs) and Langmuir probes to map the ion energy distribution and plasma parameters in the vicinity of a Faraday probe to determine the source of ion beam-current over-predictions.

Diagnostic development in the Gallimore group also includes advanced optical methods to study plasma properties. For example, they have succeeded in proof-of-concept tests of Two-Wavelength Simultaneous Laser Induced Fluorescence (TWS-LIF) techniques for characterizing Hall thruster and ion thruster erosion.

Research also includes new thruster developments. They have recently developed the gridless ion thruster, NASA-173G, which uses heritage developed from NSTAR and the P5/NASA-173 program in its design. The 173G is a hybrid between an ion thruster and a Hall thruster (patent pending). More recently, they have made ESA and retarding potential energy analyzer (RPA) measurements of the 2x2 Busek BHT-200 Hall cluster, a single cluster element, the NASA-173m, and a gridded ion source (the last in conjunction with Laser Induced Fluorescence) to compare these diagnostic techniques.

An ongoing project within the Michigan studies includes understanding ground test limitations, and, in particular, limitations associated with finite pumping speed and size of ground test chambers. They have developed a method of accurately measuring cold and hot flow pressure in a vacuum chamber and have conducted cold flow pressure maps of PEPL's LVTF and NASA GRC's VF12, and hot flow maps of the LVTF.

Future and other ongoing research in Gallimore's laboratory includes experiments with a 2x1 P5 Hall cluster (20 kW max power) including operating the thruster pair with one cathode and conducting research associated with high-Isp ion thrusters for NASA's Nuclear Space Initiative (Prometheus/JIMO).

Professor Boyd's activities involve the development of advanced computer models for analysis of plasma and gas flows in electric propulsion systems. They are developing models of EP devices to aid in thruster design and to assess lifetime issues. In addition, they are developing models of the plumes from EP devices partly to validate the device models, but also for assessment of spacecraft integration issues.

In their studies of ablative plasma thrusters, their work continues in the modeling of plumes, particularly from micro-laser-ablation thrusters. A new model for transmission-mode operation is being developed and the resulting plume simulation results are to be compared with experimental data [14]. Research also continues on the development of detailed models of micro-pulsed plasma thrusters. In addition to prediction of thruster performance, the models are being extended to include effects of nonequilibrium ionization and propellant recession [15].

In their studies of Hall thrusters, the effects of detailed xenon collision cross sections on the plume of the SPT-100 Hall thruster were assessed using data from the Express spacecraft [16]. Development also continues of a detailed 2d, unsteady model of the acceleration channel and near-field plume for simulating various Hall thrusters [17,18]. It is well known that the interaction of the Hall discharge plasma with the surrounding channel wall greatly affects the overall performance. Recently, presheath structures and near-wall effects in the acceleration channel of an anode layer thruster are being modeled using a hydrodynamic approach [19]. In a collaboration with Gallimore's group to study ground test facility limitations, the Boyd group has carried out detailed DSMC computations of cold flow expansion from the P5 Hall thruster into the PEPL vacuum chamber and have compared the predictions to measurements of the facility back-pressure [20].

The Boyd group has also carried out extensive modeling of electrostatic ion thrusters. For example, a PIC-DSMC grid optics code continues to undergo development and is being used to help design NASA's NEXT ion thruster. Based on modeling results, a set of Thick Aperture Optics (TAG) has been selected [21, 22] as a design for future testing. A detailed PIC-DSMC model is also being applied to describe the plume from the T6 hollow cathode and compared with experimental measurements [23].

Finally, a more recent focus area has been in the field of FEEP thrusters. In the Boyd group, probes are being designed to measure charge and mass of propellant droplets produced by an In-FEEP thruster that will be tested this summer at NASA-JPL. This project will also involve modeling of the Taylor-cone formation and plume structure.

D. Research at the University of Illinois

Research at the University of Illinois falls under the program headed by Professor Rodney Burton, and is focused in several aspects of vacuum arc thrusters, and pulsed plasma thrusters, including:

(i) Ion Acceleration in Vacuum Arcs. Vacuum arc thrusters (VATs) are being developed [24] to provide a highly scalable micro-propulsion system for use on small <100 kg satellites. VATs operate by producing an arc discharge between two electrodes, and produce thrust by emission of neutrals and ions from the negative electrode. Ion velocities have been measured up to 15 km/s, (aluminum) corresponding to energies over 30 eV. During VAT operation the arc is observed to attach to the cathode in highly mobile "cathode spots," each with a diameter on the order of 5 μm, as seen by scanning electron microscope images of the craters resulting during operation. These cathode spots operate at a high current density, on the order of 10^6 A/cm^2. The extreme current densities and high mobility of the cathode spots has made them difficult to model, and although they have been studied for decades [25], there is much that is not well known. The precise source of the ions, as well as their acceleration mechanism is still an open question. Three theories attempt to explain the ion acceleration. The potential hump theory postulates that after neutrals coming off the cathode are ionized, due to the difference in electron and ion mobility, a potential hump is formed, producing a local electric field in the direction of the anode. A gas dynamic theory states that the ions are accelerated by pressure differences caused by cathode and plasma heating. Finally, the Lorentz force or electromagnetic acceleration could produce the high ion velocities.

(ii) Surface Temperature Measurements. The University of Illinois and the Air Force Research Laboratory at Edwards AFB are collaborating to investigate the Teflon™ surface temperature profile during and immediately following a discharge in order to reduce the uncertainty associated with the neutral density predictions. A technique developed for crack propagation monitoring is being applied to the MicroPPT surface, which results in time-resolved temperature profiles over the course of the 10 μsec discharge. Initial data has shown that this diagnostic is able to measure surface temperature for cooling late in the pulse and after the pulse. Techniques are being investigated to measure surface temperature also during the arc. The basic technique is understood, and current efforts are finalizing the calibration methodology in order to reduce measurement uncertainties.

A MicroPPT is installed in a vacuum chamber with optical access that allows imaging of the surface onto a Mercury Cadmium Telluride photovoltaic detector. The detectors are capable of 10 MHz temporal response and are imaged directly on the propellant surface. The calibration is obtained by heating a Teflon™ sample to a known temperature while measuring the response of the detector. Full verification of the diagnostic is underway with tests determining the effects of surface roughness on the Teflon emission due to plasma exposure. In this case, a heating element is applied directly to the MicroPPT body to calibrate to both virgin and used Teflon [26].

(iii) Advanced Pulsed Plasma Thruster. PPT-11 is an advanced side-fed coaxial design that minimizes the thruster mass while maximizing thruster performance [27]. Four Teflon fuel bars are fed radially through the cathode and rest against a central anode. The total thruster wet mass is 318 g including the useable fuel mass of 70 g. Up to four Unison mica capacitors, totaling 82 μF, provide energy storage. The result of this development is a flight-capable thruster with a specific impulse bit of 20 μN-s/J, a thrust of 1.73 mN, and an I_{sp} of 1374 s. The total impulse is 943 N-s. The thruster operates at 85 W with a thrust efficiency of 13.7%. The highly repeatable thrust is approximately 70% electromagnetic. A typical system mass is 8.27 kg which includes four thrusters, propellant, spark plugs, striplines, and 70-J capacitors. PPT-11 geometry studies have been performed. Three propellant geometries, five anode designs, and three anode materials have been tested resulting in a geometry that maximizes thrust efficiency. PPT-11 is modular such that it can be utilized in a variety of small spacecraft for various mission requirements.

E. Research at the Massachusetts Institute of Technology

The MIT Space Propulsion Laboratory headed by Professor Manuel Martinez-Sanchez is engaged in several lines of research on Electric Propulsion, including:

(i) Development of Hall Thruster simulation tools. They are extending the fully kinetic PIC methodology to simulate one and two-stage Hall thrusters. Parallel work is underway to numerically investigate anomalous electron transport, and to obtain internal probe data on a Busek thruster for validation of the codes.

(ii) Hall Plume research. They are constructing a 3D Hybrid PIC plume code using an unstructured grid and allowing non-quasi-neutral regions. Particular attention is being paid to the quality of the initial plane data. This will be an integral part of the AFRL COLISEUM interactions environment. Parallel experimental measurements are being carried out on various plume parameters of a 200W thruster.

(iii) Colloid Propulsion research. They are pursuing several lines of work on colloid thrusters, including the micro-fabrication of emitter arrays. A 250 emitter 1D array is being completed, and 2D arrays of various designs are planned. This includes designs featuring “wicking” action for feeding the liquid. Research on colloid thrusters also includes source characterization, using a combination of time-of-flight and energy analysis of sprays from several liquids. The droplet, mixed and ionic regimes have been explored, and more work is planned on the last two in particular. MIT is also engaged in modeling studies of colloid thrusters. They have developed and verified a time-dependent numerical model of an electrospray emitter in the Cone-Jet regime. Extensions are planned to the ionic emission regime and to the multi-cone regime. Also in development is a particle-tracking code for the colloidal plume.

(iv) Electrodynamic Tethers. They are continuing research on simulation of the anodic end of an electrodynamic tether. This work is also of use to Langmuir probe users in the difficult meso-sonic, magnetized condition.

(v) Optimization of Mixed EP-Chemical Missions. We are developing robust EP trajectory optimizers and combining them with impulsive models for end-to-end optimization of launches to GEO which utilize EP augmentation

F. Research at Colorado State University

The Research at Colorado State University is headed by Profs. John Williams, Azer Yalin, and Paul Wilbur. Electric propulsion research at CSU concentrates on fundamental problems related to ion thrusters. A study of ion optics systems is being conducted on high specific impulse grid designs developed by the Jet Propulsion Laboratory [28]. The operational range over which an ion optics system can be run is limited in many aspects, which are classified as beamlet current limitations, backstreaming limitations, and electric field breakdown limitations. These operating limits are being investigated experimentally using sub-scale grids (gridlets) that contain a fraction of the total number of holes (typically 6 to 37 hole arrays) associated with a full ion optics system. The CSU gridlet testing facility is being used to perform experiments over a wide range of operating conditions, with control over discharge plasma potential, accel grid voltage, discharge voltage, propellant mass flow rate, neutralizer bias voltage, and neutralizer discharge power.

A study of the NASA Glenn Evolutionary Xenon Thruster (NEXT) ion optics system is being performed using the ffx code developed at CSU [29]. Specifically, we are using the ffx code to predict how the acceleration grid of the NEXT ion optics system erodes over time. We are also calculating the sputtered molybdenum flow field that is produced in the regions upstream and downstream of the acceleration grid. One use for these calculations is to determine the buildup of sputtered molybdenum on the screen grid, which can become problematic during long missions when the sputter deposited film flakes off of the screen grid and bridges between the acceleration and screen grids. The ion optics system geometry can become quite complex as it is eroded, and electrode surfaces will most often lie between mesh points. To improve calculations based on evolving surfaces using fixed mesh geometry, a method of sub-mesh grid placement is being implemented into the ffx code that not only corrects electric fields near grid surfaces, but also accurately defines surface normal vectors that evolve over time. The surface normal vectors are calculated based on the local center of mass in the region of each cell, and actual distances to sputter eroded grid surfaces and applied grid potentials are used in solving Poisson's equation. Charge exchange ion-induced erosion of grid surfaces is calculated by tracking charge exchange ions from their point of origin to the point where they strike a surface. Both the energy and angle of incidence of the charge exchange ion at the point of impact are used to calculate the sputter rate.

A study of high-energy ions produced nearby hollow cathodes is being performed using a 30-cm diameter prototype discharge chamber [30]. Specifically, ion energy is being characterized using a remotely located, electrostatic energy analyzer. A very complex structure of the ion energy distribution function has been observed that is in general agreement with previous observations from many earlier works. Observations, which are in general agreement with the literature, include the measurement of ions that have "through anode" energies and beyond, that have higher ion energies occurring as flow rate is reduced, and that have more energetic ion production at higher discharge currents. All of these observations are also in line with results from long term life tests of hollow cathode-equipped ion thruster systems, which exhibit slow erosion of hollow cathodes and components located nearby that is presumably caused by sputtering due to energetic ion bombardment. Most studies of hollow cathodes have concentrated on devices operated outside of discharge chambers where they are more readily accessible. This study is different in that it is being performed with the hollow cathode located within a 30-cm diameter discharge chamber. Very interesting results obtained in recent experiments at high discharge currents show the ion energy distribution varying widely when measured at different zenith angles and at different positions near the hollow cathode. Specifically, few high-energy ions are seen on-axis, but many are seen at moderate (~20° and higher) zenith angles and from regions up to 5 cm from the cathode. This observation is different than those made on hollow cathodes operated outside of a discharge chamber.

A study is being performed to measure the differential sputter yield of materials important to high specific impulse ion thrusters [31]. The heart of the technique that is being utilized is a quartz crystal monitor that is swept at constant radial distance from a small target region where a high current density xenon ion beam is aimed. Differential sputtering yields are being measured over a full 180° arc in a plane that includes the beam centerline and the normal vector to the target surface. Sputter yield results are being collected over a xenon ion energy range from 0.2 to 10 keV and over an angle of incidence range from 0º to 70° for targets consisting of molybdenum, titanium, solid (Poco) graphite, pyrolytic graphite, carbon-carbon composites, aluminum, stainless steel, and flexible graphite (grafoil). Curve fits to the differential sputter yield data are being cataloged, and they should prove useful to analysts interested in predicting the erosion profiles of ion thruster components and determining the directions where the erosion products escape to or surfaces were they deposit upon.

A study is being performed to evaluate the use of cavity ring-down spectroscopy (CRDS) to determine sputtering behavior and gridlet erosion characteristics. CRDS is an ultra-sensitive laser-based absorption diagnostic that has been used extensively by chemists. In CRDS, an optically absorbing sample is housed within a high-finesse optical cavity, in which a probe laser pulse bounces back and forth many times. This multi-pass technique enables very sensitive concentration measurements. In contrast to optical emission spectroscopy (OES) and laser induced fluorescence (LIF), CRDS has the additional advantage that the results are directly quantitative and do not require knowledge of quenching rates or excitation coefficients. We have performed spectral simulations that predict our detection limit for titanium and molybdenum will be at concentrations of $\sim 10^5$ cm^{-3} over a 1 cm path length, which is many orders of magnitude below typical concentrations produced in our sputter test facility. We are also interested in studying carbon erosion. While C is difficult to measure with CRDS, it should be possible to more easily measure species such as C_2, C_3, etc. Interestingly, recent research at UCSD shows that atomic C comprises only a small fraction of the total carbon sputtered by xenon at low energies [32]. A set of experiments is being planned for later this summer to experimentally demonstrate the CRDS sputter measurement concept on titanium, molybdenum and carbon targets.

G. Research at the University of Washington

Research in electric propulsion at the University of Washington focuses mainly on Mini-magnetospheric plasma propulsion (M2P2), which seeks to tap the energy of space plasma by deflection of an enhanced magnetic field to provide spacecraft propulsion. Experiments over the last year have demonstrated the ability of a prototype plasma source to produce hot (20 eV) plasma in argon at densities of 10^{19} cm^{-3} using about 1.5-kWe power. This plasma is expected to produce enhancement of the magnetic field, which if deployed in space could intercept ~1 N of force. To test its ability of deflecting such energetic plasma, deflection tests of surrogate solar wind plasma using a 200-kWe plasma source have been undertaken and results will be presented at this conference.

Langmuir probe studies have been carried out for measurements of the plasma density near the M2P2 magnet. The solar wind surrogate of high power source (HPS) is able to produce deep penetration of the plasma into the magnetic field if the plasma source on M2P2 is not operating. With M2P2 operating, about 66% of the plasma is screened out, which an amazing achievement is given the difference of two orders of magnitude in power between the two plasma systems. Higher efficiencies in deflection occur as the M2P2 field strength is increased. These early demonstrations motivate continued research in this advanced future propulsion concept.

H. Research at Arizona State University

The electric propulsion program at Arizona State University primarily concentrates in the theoretical analysis of high power electromagnetic devices, such as MW-class magnetoplasmadynamic (MPD) thrusters operating with and without applied magnetic and the Pulsed Inductive Thruster (PIT). During this past year efforts have focused on utilizing a magnetohydrodynamic code, MACH2 [33] to simulate operation of the PIT in order to bilaterally validate the model and experimental data. MACH2 is a time-dependent, two-dimensional, axisymmetric, multi-material code that can be applied to problems of complex geometries due to its multi-block structure.

Computations are typically performed for the range of available charge voltage and propellant mass. Specifically, experiments addressed a range of energy levels between 900J and 1764J with propellant mass variation from 0.75 mg to 9.2 mg. For each pair, data for the impulse were provided which in turn produced the range of specific impulse and efficiency values. MACH2 was invoked to compute all the different arrangements for a full range comparison of impulse verses specific energy. The computed results correlate very well with the experimental values. For example, MACH2 computed impulse values for 900J cases exhibit an overestimation of about 10% when compared to experimental results. This discrepancy is partially attributed to an experimentally observed critical-mass value below which incomplete breakdown was observed along with the consequent reduction in impulse. Even though the code cannot address breakdown physics, this implicit incomplete coupling of plasma and magnetic flux is partially reflected by the computations as indeed efficiency is decreasing with decreasing propellant mass value. However, the magnitude of this reduction is not fully captured by the code's physical models and thus the overestimation. It is of interest to note though, that MACH2's partial capture of this critical-mass trend is indicative of additional influencing processes other than breakdown behavior.

Additional simulations [34] address the influence of a restrictive vacuum tank used for the experiments along with the influence of the mass-injection scheme relative to uniform propellant mass distribution over the discharge coil utilized to obtain the abovementioned results. In both cases the influence on the integrated impulse values of such operating variations is insignificant.

Significant MACH2 upgrades are being constructed in order to address operation at higher energy levels operating with ammonia propellant that exhibited the elevated efficiency values. These include construction of an appropriate equation-of-state model and incorporating the influence of a moving conducting plasma in the LRC circuit used to emulate the PIT's circuit powertrain. Such comparisons will allow valuable insights in deciphering the distinction between the elevated performances measured when operating with ammonia propellant as opposed to all other propellants.

I. Research at the Princeton Plasma Physics Laboratory

We continued our development of the cylindrical Hall thruster for 100 W and lower input power range. A small 2.6 cm diameter thruster, which was designed by scaling down from a larger 9 cm cylindrical Hall thruster [35], already exhibited state-of-the-art performance in the power range 50-200 W [36]. Because of its larger volume to surface ratio, the cylindrical thruster might lead to longer lifetime than conventional coaxial low power Hall thrusters. Our present research is aimed to understand better the physics of the cylindrical Hall thruster in order to optimize its performance in low input power range (>100W). Efficient thruster operation in this power range might be achieved because of the unusually high ionization efficiency (>90%) in the cylindrical Hall thrusters [35,37]. The larger aspect ratio of the cylindrical channel compared to the coaxial channel of the same outer diameter is not likely the full cause of the high ionization [37,38]. The high ionization may also be due to electron or ion trapping. A strong dependence of the ionization efficiency and stability of the thruster discharge on the shape of the magnetic field in the cylindrical channel also suggests the presence of electron and ion traps [35-38].

The use of emissive and non-emissive conductive electrodes and dielectric spacers placed in the Hall thruster channel might help maintain a narrow plasma jet from the thruster, provide high ionization efficiency for variable thrust operating regimes, and allow for a longer thruster lifetime. A new 12 cm diameter Hall thruster was designed specifically for studies of the segmented electrode effects and their scaling for high power thrusters. We are currently studying the operation of this thruster in a conventional non-segmented configuration. The thruster was operated in the large vacuum facility upgraded with cryogenic pumps. Thruster performance and parameters of the plasma flow are measured by new and upgraded plume and movable probe diagnostics. The thruster already demonstrated efficient operation measured in terms of propellant and current utilization efficiencies in the input power range of 0.5-3.5 kW [39]. We have recently conducted an experimental study of the acceleration region in this thruster [40]. Using a novel segmented shielded probe in the discharge voltage range of 200-600V and the input power range of 1-3.5 kW, we measured plasma parameters while incurring only small perturbations of the thruster discharge. The results of these measurements are qualitatively consistent with theoretical predictions. New results regarding the effect of the discharge voltage on the length of the acceleration region and the maximum electron temperature can provide a better understanding of Hall thruster physics [40].

J. Research at Princeton University

Research at Princeton University's Electric Propulsion and Plasma Dynamics Lab (EPPDyL) has focused on two general areas: i) fundamentals of plasma propulsion and ii) proposing and developing new propulsion concepts.

In the first area, a detailed experimental investigation of the dynamics of current sheets has provided an experimentally supported explanation [1] of the canting phenomenon that is ubiquitous in electromagnetic pulsed plasma thrusters (EM-PPTs). A new study focusing on characterizing the permeability of these current sheets has produced detailed current sheet visualization through high spatial resolution B probing and yielded insight into the nature of these current structures [2,3]. Both phenomena, canting and permeability have direct impact on thruster efficiency.

Ongoing studies (of high-power steady-state lithium Lorentz Force Accelerators (Li-LFAs) have focused on measured performance scaling [4], understanding of multi-channel cathode mechanisms, multi-wavelength pyrometry [5], plume characterization using QCM probes and detailed numerical simulations [6].

In the area of new concepts, research on the newly discovered phenomenon of ion acceleration with beating electrostatic waves has evolved from theoretical calculations [7] to experimental verification [8,9]. Another new concept called Faraday Accelerator with RF-assisted Discharge (FARAD) was recently proposed by EPPDyL and is being studied experimentally. It relies on electrode-less pulsed inductive current sheet acceleration in a plasma produced by a helicon source.

A fundamental scaling parameter for liquid capillary flows was recently found and experimentally verified [10] and has applications in designing passive mass feeding system for micropropulsion. A recently proposed discharge initiation system that uses laser pulses to thermionically release electrons into the electrode gap, is studied as a replacement for the sparkplugs used in present PPTs. The present investigation [11] focuses on the fundamentals of photo-induced surface-assisted discharge initiation and has yielded an analytical model that has been verified experimentally.

K. Research at Kettering University

Electric propulsion research at CPDL is focused on hydrodynamic model development for partially ionized gas flow processes inside the thruster channel. These studies are in three categories: (1) Understanding high specific impulse stationary Hall effect thrusters for improved performance. (2) Electrode model for magneto-plasmadynamic thruster. (3) Sheath model for low-pressure collisional plasmas. Specifically for Hall thrusters, a two-dimensional three-fluid finite element based model has been developed incorporating neutral dynamics, collisions and wall interactions [52-55]. Among many reasons limiting the efficiency and lifetime of a Hall thruster, the most critical are the ionization and recombination processes inside the thruster channel and the wear of the surface layer of the ceramic walls due to the plasma-wall interactions. In the hydrodynamic model, the effect of ionization and recombination has been included as a function of electron temperature based on the experimental data. The neutral dynamics is included only through the neutral continuity equation in the presence of a uniform cold neutral flow. The electrons are modeled as magnetized and hot, whereas ions are assumed unmagnetized and cold. Simulation results are interpreted in the light of experimental observations and available numerical solutions in the literature. The plasma-wall interaction has been modeled as a function of wall potential, which in turn is determined by the secondary electron emission and sputtering yield. Considerable changes in the plasma density, the potential and the azimuthal electron velocity are found due to wall interactions in the acceleration region. The self-consistent calculation displays, on the one hand, a direct correlation between the ion and neutral densities and on the other, a direct correlation between neutral density and neutral velocity. The subsequent generalization of the model is underway.

For the magnetoplasmadynamic (MPD) thrusters, CPDL is developing a finite element based hydrodynamic model for understanding the underlying physics [56] and also uses MACH2 code developed by AFRL for design purposes [57]. For an improved electrode model for MPDs, the plasma-sheath dynamics under low pressure is also being studied both analytically and numerically [58-60]. As the sheath forms, the analytical model tries to understand the acceleration of the sheath edge as a top-heavy equilibrium [58]. In the sheath frame ions are accelerated towards the wall–sheath boundary in ion response to the electric field. In such a situation sheath may become unstable. The sheath instability is examined as the Rayleigh–Taylor instability and RT growth rate is compared with the reported sheath instability in the literature. The numerical model is a one-dimensional subgrid embedded finite element formulation [59,60]. The model incorporates space charge effect throughout the whole plasma and the sheath region using three-fluid equations. Secondary electron emission is not considered. A third order temperature dependent polynomial is used to self-consistently calculate the rate of ionization in the plasma dynamic equations. The applications for the model include dc and rf sheath inside a glow discharge tube where the noble gas is immobile, and a partially ionized plasma sheath inside an electric propulsion thruster channel in which the gas flows. The dc and rf sheath models compare reasonably well with available data in the literature. For the very low-pressure thruster, the electron and ion number density profiles near the sheath show their usual distribution. The ion velocity keeps increasing in the bulk plasma and crosses the characteristic velocity given by Godyak and Sternberg near the pre-sheath. The sheath potential compares well with available experimental data. The neutral density showed anomalous behavior near the wall. The model is currently being generalized to incorporate wall interactions and magnetic field for specific electric propulsion applications.

L. Research at Virginia Polytechnic Institute

Electric propulsion research activities at Virginia Tech in the past year include experimental and modeling investigations of low energy ion sputtering in ion thrusters, development of an immersed finite element particle code for electric propulsion modeling, and development of a virtual design environment for electric propulsion.

Computer particle simulation based modeling is becoming an ever more important element in electric propulsion research and development activities. However, in order to apply particle simulations as an engineering design tool for electric propulsion, one must overcome at least two major challenges. First, one needs to be able to build up a code that is sophisticated enough so the complex geometry associated with a thruster can be modeled properly and yet computationally efficient enough so large-scale 3-D particle simulations can be performed routinely. Second, one needs to be able to quickly transform "data rich" simulation results to "information rich" for engineering applications. In this paper, we present a brief overview on two activities at Virginia Tech that attempt to address these two challenging issues.

In the first activity, supported by Air Force Research Lab AFRL), we recently developed a new particle simulation algorithm using the immersed finite element (IFE) to solve the electric. Complex geometries are usually handled by using unstructured grids to body fit the boundary. While such a method is highly accurate for solving electric field, it also can be computationally very expensive for tracing particles and performing particle-grid interpolations. Our new algorithm maintains a Cartesian base mesh for particle-in-cell. Each Cartesian cell contains a secondary mesh of 5 tetrahedrons, which are used by the field solver field. The electric field is solved as an interface problem. The trial functions for interface cells are constructed using only physics based jump conditions. This method offers many advantages over existing algorithms. First, since the electric field is solved for both inside and outside of the object with the correct physics maintained at interface, the material property effects are explicitly included. Second, since the numerical mesh is generated independent of object boundary, one can use a Cartesian mesh for complex geometric interface and same mesh to handle time-varying interface (without using mesh refinement). Hence, PIC simulations can be performed almost as efficiently as a standard PIC code. This new field-solving algorithm has been incorporated into two particle simulation models, one for simulation of electric thruster plume spacecraft interactions under AFRL's coliseum project and the other for simulation of ion thruster optics [61,62].

In the second activity, we recently developed a new, cross-platform visualization and analysis tool, capVTE [63]. capVTE can be used with both virtual reality environments, such as CAVE (Cave Automatic Virtual Environment), and regular desktop/laptop machines. It offers immersed visualization for users inside CAVE where users would be able to "walk" into 3D stereographic representation of simulation data (Figure 2, left panel). It also offers a shared, collaborative environment to allow remotely connected users to interact with each other over same data objects. The collaborative environment is done using a client/server interface. One user selects to be the server, and all other users connect to him. Remote network clients can interact over the same visualization from the capVTE windows on their own machines. When any user performs an action that changes the visualization domain, the change is communicated through the network and so every user observes the same change. Additional features which would allow remote users to communicate using text messages in a way very similar to the Instant Messenger will be included in the near future. Our eventual goal is to combine this virtual environment with first principle based modeling to develop a virtual design laboratory for electric propulsion.

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[1] Blandino, J., Roy, T., and Gamero-Castano, M., AIAA-2003-4849, 39th AIAA Joint Propulsion Conference, July 2003.

[2] Blandino, J., Mueller, J., Bame, D., and Green, A., AIAA-2003-4719, 39th AIAA Joint Propulsion Conference, July 2003.

[3] Siegel, A. and Tucker, A., WPI MQP Report JB3-ORBT, October 2002.

[4] Siegel, A. and Blandino, J., AIAA-2003-4577, 39th AIAA Joint Propulsion Conference, July 2003.

[5] Gatsonis N.A., Suryuali, A., AIAA Paper no 2003-5019, July 2003.

[6] Gatsonis N.A., and Spirkin, A., AIAA- Paper No. 2003-3896, July 2003.

[7] Gatsonis, N.A., Partridge, J., Blandino J., Pencil, E., AIAA Paper No 2003-5172, July 2003.

[8] Wheelock, A., Gatsonis, N.A., and Cooke, D.L. AIAA 2003-5148, 39th AIAA Joint Propulsion Conference, July 2003.

[9] M. A. Cappelli, N.B. Meezan, and N. Gascon, AIAA-2002-0485, Aerospace Sciences Meeting, Reno, NV, January 2002.

[10] C. Thomas, N. Gascon, and M. Cappelli, AIAA-2003-4854, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.

[11] N. Gascon, N. Meezan, C. Thomas and M. Cappelli, AIAA-2003-4857, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.

[12] 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.

[13] E. Fernandez and M. A. Cappelli, 42nd Annual Meeting of the Division of Plasma Physics, American Physical Society, Quebec City, Quebec, October 23-27, 2000. See also Bull. Am. Phys. Soc. **45**, 166, 2000.

[14] Keidar, M. and Boyd, I.D., AIAA 2003-4567, 39th AIAA Joint Propulsion Conference, July 2003.

[15] Keidar, M. and Boyd, I.D., AIAA 2003-5166, 39th AIAA Joint Propulsion Conference, July 2003.

[16] Boyd, I.D. and Dressler, R.A., Journal of Applied Physics, Vol. 92, 2002, pp. 1764-1774.

[17] Koo, J.W. and Boyd, I.D., IEPC Paper 03-071, March 2003.

[18] Koo, J.W. and Boyd, I.D., AIAA Paper 2003-4705, 39th AIAA Joint Propulsion Conference, July 2003.

[19] Keidar, M. and Boyd, I.D., AIAA Paper 2003-4701, 39th AIAA Joint Propulsion Conference, July 2003.

[20] Boyd, I.D., Cai, C.P., Walker, M., and Gallimore, A.D., 23rd International Symposium on Rarefied Gas Dynamics, July 2002.

[21] Emhoff, J.W., Boyd, I.D., and Shepard, S.P., IEPC Paper 03-110, March 2003.

[22] Emhoff, J.W. and Boyd, I.D., AIAA Paper 2003-4868, 39th AIAA Joint Propulsion Conference, July 2003.

[23] Crofton, M.W. and Boyd, I.D., AIAA 2003-4171, 39th AIAA Joint Propulsion Conference, July 2003.

[24] J. Schein, et. al, Alameda Applied Scientific Corporation, IEPC-01-228, 27th Int. Electric Propulsion Conf., Pasadena CA, Oct 2001.

[25] J.M. Lafferty, Ed., Vacuum Arcs, Theory and Application, John Wiley, 1980, pp. 120-168.

[26] Antonsen, E. L., et al., IEPC-03-290, 28th Int. Electric Propulsion Conf., Toulouse, FR, Mar 2003.

[27] Laystrom, J., M.S. Thesis, University of Illinois, Department of Aerospace Engineering, 2003.

[28] D.M. Laufer, J.D. Williams, C.C. Farnell, and P.J. Wilbur, 39th Joint Propulsion Conference, Huntsville, AL, July, 2003.

[29] C.C. Farnell, J.D. Williams, and P.J. Wilbur, 39th Joint Propulsion Conference, Huntsville, AL, July, 2003.

[30] C.C. Farnell, J.D. Williams, and P.J. Wilbur, IEPC-03-072, Int'l Electric Propulsion Conference, Toulouse, France, 2003.

[31] John D. Williams, Michael M. Gardner, Mark L. Johnson, and Paul J. Wilbur, IEPC-03-2003, Int'l Electric Propulsion Conference, Toulouse, France, 2003

[32] R. P. Doerner, D. G. Whyte, and D. M. Goebel, J. Applied Physics, V. 93, No. 9, 2003).

[33] Peterkin, R.E., Jr. and Frese, M.H., MACH: A Reference Manual – 1st Edition, Air Force Research Laboratory, Kirtland AFB, New Mexico, September 14, 1998.

[34] Mikellides, P.G., IEPC-0135, International Electric Propulsion Conference, Toulouse, France, March 2003.

[35] Y. Raitses and N. J. Fisch, Phys. Plasmas **8**, 2579, 2001.

[36] A. Smirnov, Y. Raitses and N. J. Fisch, J. Appl. Phys. **92**, 5673, 2002.

[37] A. Smirnov, Y. Raitses and N. J. Fisch, J. Appl. Phys. **94**, 2003.

[38] A. Smirnov, Y. Raitses and N. J. Fisch, AIAA paper-2003-5000, 39th AIAA Joint Propulsion Conference, July 2003.

[39] Y. Raitses, D. Staack, A. Dunaevsky, L. Dorf and N. J. Fisch, IEPC paper 03-0139, the 28th International Electric Propulsion Conference, Toulouse, France, March 2003.

[40] Y. Raitses, D. Staack and N. J. Fisch, AIAA paper-2003-5153.

[41] T.E. Markusic and E.Y. Choueiri IEPC-03-293, 28th Int. Electric Propulsion Conf., Toulouse, FR, Mar 2003.

[42] J.W. Berkery and E.Y. Choueiri, AIAA-2002-4120.

[43] J.W. Berkery and E.Y. Choueiri, IEPC-03-307, 28th Int. Electric Propulsion Conf., Toulouse, FR, Mar 2003.

[44] A.D. Kodys, L.D. Cassady and E.Y. Choueiri. AIAA-2003-4842, 39th AIAA Joint Propulsion Conference, July 2003.

[45] L.D. Cassady and E.Y. Choueiri, IEPC-03-79, 28th Int. Electric Propulsion Conf., Toulouse, FR, Mar 2003.

[46] K. Sankaran, S.C. Jardin, and E.Y. Choueiri, AIAA 2003-4843, 39th AIAA Joint Propulsion Conference, July 2003.

[47] R. Spektor and E.Y. Choueiri, IEPC-01-209.

[48] R. Spektor and E.Y. Choueiri, AIAA-2002-3801.

[49] R. Spektor and E.Y. Choueiri, AIAA-2003-4994, 39th AIAA Joint Propulsion Conference, July 2003.

[50] K.A. Polzin and E.Y. Choueiri, IEPC-03-64.

[51] J.E. Cooley and E.YU. Choueiri, AIAA-2003- 5027.

[52] S. Roy and B.P. Pandey, Journal of Plasma Physics, 68 (4) p. 305-19 (2002).

[53] S. Roy and B.P. Pandey, Physics of Plasmas **9**, 4052-60, 2002.

[54] S. Roy and B.P. Pandey, AIAA-2003-0493, 39th AIAA Joint Propulsion Conference, July 2003.

[55] S. Roy and B.P. Pandey, Journal of Propulsion and Power, (in press, 2003).

[56] K.J. Berry and S. Roy, AIAA-2001-0200.

[57] S. Roy, P. Mikellides and D.R. Reddy, AIAA-2002-0917.

[58] S. Roy, B.P. Pandey, J. Poggie and D. Gaitonde, Physics of Plasmas **10**, 2578-85, 2003.

[59] S. Roy and B.P. Pandey, AIAA-2002-2169.

[60] B.P. Pandey and S. Roy, Physics of Plasmas **10**, 5-9, 2003.

[61] J. Wang, R. Kafafy, and L. Brieda, AIAA 2003-4874, 39th AIAA Joint Propulsion Conference, July 2003.

[62] R. Kafafy, T. Lin, and J. Wang, AIAA 2003-5194, 39th AIAA Joint Propulsion Conference, July 2003.

[63] L. Brieda, J. Pierru, R. Stillwater, and J. Wang, AIAA 2003-5020, 39th AIAA Joint Propulsion Conference, July 2003.