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Abstract

The NASA Hall thruster program currently supports a number of tasks related to high power thruster development for a number of customers including the Energetics Program (formerly called the Space-based Program), the Space Solar Power Program, and the In-space Propulsion Program. In program year 2002, two tasks were central to the NASA Hall thruster program: 1.) the development of a laboratory Hall thruster capable of providing high thrust at high power; 2.) investigations into operation of Hall thrusters at high specific impulse. In addition to these two primary thruster development activities, there are a number of other on-going activities supported by the NASA Hall thruster program. These additional activities are related to issues such as high-power power processor architecture, thruster lifetime and spacecraft integration.

Introduction

The NASA Hall thruster program at the Glenn Research Center (GRC) currently supports a number of tasks related to high power thruster development for a number of customers including the Energetics Program (formerly called the Space-based Program), the Space Solar Power Program, and the In-space Propulsion Program. High power thruster development is being emphasized because recent mission analyses have shown a need for higher power electric propulsion systems for both Earth orbital and deep space applications. However, these different applications require propulsion systems with different optimal characteristics. Earth orbital applications such as space tugs, spacecraft orbit insertion, etc. benefit from high thrust electric propulsion systems for timely space transfers. In contrast, deep space missions typically have large delta V requirements necessitating high specific impulse.¹⁻¹⁰ For recently considered power rich spacecraft architectures, both high power and high specific impulse propulsion systems are required.¹¹ The application of Hall thrusters to either mission type requires substantial technology advancements from state-of-the-art (SOA) thrusters.

In program year (PY) 2002, two tasks were central to the NASA Hall thruster program: 1.) the development of a laboratory Hall thruster capable of providing high thrust at high power; 2.) investigations into operation of Hall thrusters at high specific impulse.

Specifically the first task resulted in investigations of the issues associated with scaling a single thruster to power levels substantially in excess of the SOA. A 50-kW class Hall thruster was designed, built and operated over the range of 9-72 kW. The second task has focused on investigating factors critical to high specific impulse operation. This year the investigation has considered the role of magnetic field topography on high voltage operation.

In addition to these two primary thruster development activities, there are a number of other on-going activities supported by the NASA Hall thruster program. These additional activities are related to issues such as thruster lifetime, high-power power processor architecture and spacecraft integration. Thruster lifetime issues were investigated by considering the impact of Hall thruster operation at high voltage on thruster lifetime. Breadboard power system tests were conducted with a single power converter that may be suited for high-power power processing unit (PPU) architecture studies. Impedance measurements of a Hall thruster were made in an effort to develop an electrical model of a Hall thruster to enable optimum and cost effective PPU design. Finally, a new effort to consider the dynamic electrical behavior of Hall thruster discharges was initiated. This was deemed necessary due to the importance of electromagnetic interference (EMI) concerns as a spacecraft integration issue. A detailed overview of each of these activities and their current status are included in this report.

High Power-High Thrust Performance

Mission planners for future NASA applications have considered Hall thruster propulsion systems up to megawatt class power levels. These studies have shown that Hall thrusters offer a unique combination of thrust, specific impulse, and efficiency that make them well suited for Earth-orbital applications and other applications involving significant gravity wells.^{4,7} Two technical approaches to developing high power Hall propulsion systems have been considered: building a large monolithic, high-power thruster of the desired power level or building an array of smaller thrusters that collectively operate at the desired power level.^{12,13} Due to ground testing constraints,^{14,15} likely spacecraft architectures and reliability/redundancy issues a multiple thruster approach would likely be preferred, especially at megawatt power levels. However, the maximum size for any single thruster has not been adequately investigated, so it is yet unclear what number of thrusters would be required for high power missions. Clearly, a megawatt cluster of 1 kW Hall thrusters (the current SOA) is not the answer, as this would result in a system consisting of 1000 engines. A more manageable and reasonable approach suggests clusters of no more than ten engines, or 100 kW per thruster for a megawatt class mission. The current effort seeks to experimentally investigate the issues associated with scaling a single thruster to power levels substantially in excess of the 1 kW SOA. Synergistic work funded by the United States Air Force is concurrently investigating issues of developing clusters.¹³ The understanding gained in both programs will significantly advance the mission applicability of high power Hall thruster propulsion systems.

The NASA Glenn Research Center (NASA GRC) experimental program utilized the laboratory model NASA-457M thruster (Figure 1). The thruster was designed and fabricated to nominally operate at 50 kW and 100 A. The initial test program focused on establishing the operational characteristics and performance of the thruster at conservative power densities to identify any potential design deficiencies and to evaluate the viability of the scaling relationships used to design the thruster. Subsequent tests investigated thruster performance over an extended range of operating conditions. The results, as can be seen in Figure 2, demonstrated operation up to 72 kW and 3 N of thrust. At the design point of 500 V, 100 A discharge specific impulse and efficiency were 2747 seconds and 63%, respectively. Total specific impulse and efficiency with a non-optimized cathode were 2528 seconds and 56%, also at 500 V, 100 A. Thruster operation was stable over all conditions; the maximum power demonstrated thus far being limited only by available power supplies. Manzella, et al. has a complete description of the thruster and test results.¹⁶

An extensive follow-on test effort is planned. This will include an attempt to evaluate the influence of the test facility on the measured results as well as additional efforts to maximize the performance envelope of the NASA-457M with regard to thrust density and power density. Very high thrust density operation will be investigated by considering operation at discharge currents much greater than 100 A at discharge voltages of 150-200 V. High power density operation will also be revisited at voltages in excess of the nominal 500 V design point.



Figure 1 – NASA-457M (large thruster in the center), NASA-120M (small thruster in the center), SPT-100 (left), T-160E (right).

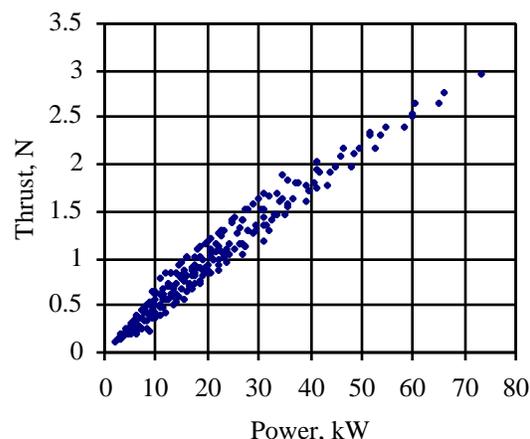


Figure 2 – NASA-457M Hall thruster demonstrated operating range.

These efforts will focus on the effect of an auxiliary magnetic trim coil incorporated in the NASA-457M. Other NASA GRC funded efforts have recently shown how similar trim coils can enable efficient operation over a wide range of operating conditions.^{17,18}

Previous tests on smaller thrusters at NASA GRC have shown maximum discharge efficiencies at discharge voltages of 500 to 800 V depending on the flow rate.^{19,20} Operation up to 1000 V and 100 kW will be investigated in order to establish maximums with regard to efficiency and specific impulse for the NASA-457M. These results will be incorporated into the findings from the high specific impulse work to be described subsequently.

50 kW Hall Thruster Development

This development effort is sponsored by the In-Space Program and is developing a 50 kW-class Hall propulsion system through contract with industry. In February 2001, NASA released a request for offer (RFO) for the design and development of a 50 kW Hall thruster that could minimally provide 2.5 N of thrust at 50 kW using xenon as a propellant with a target thruster efficiency of at least 60%.

Proposals were received, evaluated and Phase I design awards were made to General Dynamics and Busek Co. Due to funding limitations, only the General Dynamics Phase II fabrication option was exercised. General Dynamics offered two concepts including an SPT-type device and a SPT/TAL hybrid device. These proposed devices have been designed with an aggressive power density to enhance performance and reduce thruster mass. Typical Hall thruster power densities are nominally 0.55 W/mm² whereas the thrusters being considered will have a nominal power density of 1.1 W/mm².

In PY2002, funding constraints limited the scope of this effort to the fabrication of these devices. In PY2003, the functionality and performance of both thrusters will be evaluated. The thermal design will be verified and feasibility of the elevated power density assessed.

High Specific Impulse Performance

The Hall thruster program at NASA GRC has in recent years awarded several contracts to explore extending the operational envelope of Hall thrusters from the current SOA. These efforts have included investigations of operating thrusters at specific impulses (Isp) as low as 1000 seconds¹⁷ and as high as 4100 seconds.¹⁹⁻²¹

Extending the operational envelope of Hall thrusters will benefit the two most prevalent trends in the

community today, multi-mode and high power thrusters. For multi-mode thrusters, developing an understanding of the processes involved has the potential to lead to Hall thrusters that operate at Isp and efficiencies comparable to ion thrusters while offering the benefits of operating the same thruster in high thrust mode at reduced Isp (~1000 seconds). For high power thrusters, developing the design knowledge to extend the efficient operating range could be vitally important in controlling waste heat. A 50 kW Hall thruster utilizing standard design philosophies will most likely be about 60% efficient, which translates to as much as to 20 kW of waste heat that must be radiated or conducted away from the thruster. Clearly, the ability to increase the efficiency of a high power Hall thruster beyond the SOA would be beneficial to spacecraft integration issues.

In the high Isp regime, contracts were awarded in previous years to investigate Hall thruster performance characteristics at Isp's greater than 3000 seconds. The first supplier was the Boeing Corporation, which through subcontract to TsNIIMASH delivered the D-80 anode layer thruster.²⁰ The Atlantic Research Corporation supplied the second thruster, through subcontract to Fakel. This device was a magnetic layer thruster designated the SPT-1.¹⁹ The third supplier was the Busek Co., which built the BHT-HD-1000, also a magnetic layer thruster.²¹ The thrusters have been operated at maximum voltages of 1700 V, 1250 V, and 1000 V for the D-80, SPT-1 and BHT-HD-1000, respectively. The D-80 demonstrated an Isp range of 1600-4100 seconds, the SPT-1 a range of 1600-3700 seconds and the BHT-HD-1000 a range of 1600-3300 seconds. Each thruster exhibited a range of voltages where the anode efficiency was maximized. This voltage was between 500-800 V depending on the mass flow rate. Precise evidence for this peak efficiency was not identified, but it was likely attributable to either increased electron current due to insufficient magnetic trapping or increased production of multiply-charged species due to the high voltages.

Building on these efforts, the objectives of NASA PY2002 and beyond are to: 1) identify the physical mechanisms that result in this maximum efficiency with voltage, and 2) develop the design tools necessary to extend efficient operation in excess of the 800 V ceiling recently observed. To achieve these goals, internal GRC efforts are underway as well as investigations through a grant with the University of Michigan^{18,22} and through an NRA with MIT and Busek.²³

In conjunction with the University of Michigan, a 5 kW high voltage thruster designated the NASA-173M V.1 has been constructed and is shown in Figure 3. Initial testing has concentrated on characterizing the

performance and identifying design variables most likely to increase efficiency through improvements. A follow on thruster designed entirely at GRC, the NASA-173MV.2, is currently in fabrication and scheduled for testing in Fall 2002.



Figure 3 – Studio portrait of the NASA-173M V.1.

Recent results from the NASA-173M V.1 operating at 300-1000 V and 5 mg/s are shown in Figure 4.¹⁸ The figure shows two sets of data, with and without a trim coil energized. When there is no trim coil, only the inner and outer coils are used (the traditional design), the previously observed peak efficiency is found. With the trim coil energized, the efficiency is maintained at >50% above 600 V, demonstrating that efficient Hall thruster operation is possible at high voltage when the magnetic field is tailored for the operating point. Similar investigations at higher flow rates, and correspondingly higher efficiencies, are planned for the NASA-173M V.2 in coming months.

Work beyond PY2002 will focus on characterizing the plasma parameters of the NASA-173M thrusters using several diagnostics to assess what effects changes in the thruster are having on performance. These diagnostics will likely include the use of ion current density probes, and energy diagnostics such as ExB probes or ion energy analyzers. Internal plasma diagnostics using a high-speed probe system at the University of Michigan are also planned.

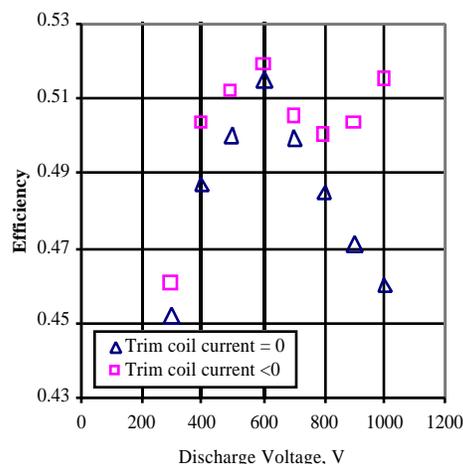


Figure 4 – Efficiency versus voltage for the NASA 173M V.1 operating at 5 mg/s.

High Voltage Thruster Life

In 1999, NASA GRC began investigating Hall thrusters with specific impulses greater than the 1500 to 1700 seconds of SOA thrusters.^{19-22,24} This increase in specific impulse over conventional xenon Hall thrusters was achieved by increasing discharge voltages from 300 V up to 1700 V. Operation at these elevated discharge voltages substantially increased the kinetic energy of the ions produced during thruster operation. At any discharge voltage, some small fraction of the ions accelerated by the thruster impinge upon the thruster itself, eroding critical components, eventually causing the thruster to wear out. While experiments have shown this in the laboratory at voltages of 300-500 V, the effect of discharge voltages in excess of 500 V on thruster lifetime has not been investigated.

The objective of the current investigation was to evaluate the effect of high voltage operation on thruster erosion. Specifically, a D-80 anode layer thruster was operated at 700 V and 4 A. A 700 V discharge voltage was selected because a previous performance investigation demonstrated maximum efficiency at voltages between 500-800 V.²⁰ A 4 A discharge current was selected for extended operation because this was the maximum value that could be achieved while maintaining the desired steady state thermal conditions. The anode efficiency and specific impulse at this operating point were 57% and 2625 seconds, respectively. While efficiency over 70% and specific impulse over 4000 seconds were demonstrated at higher discharge voltages and currents, high thruster temperature prohibited operation for extended periods of time. The thruster was operated for a total duration of 1200 hours in this investigation. Erosion of critical thruster components was evaluated every 300 hours.

The thruster exhibited asymmetric erosion that exposed the magnetic poles between the 600 and 900 hour increment (Figure 5). Even as the magnetic poles were exposed the robustness of the thruster was demonstrated by no change in operating parameters. Jacobson has a complete description of the thruster and test results.²⁵

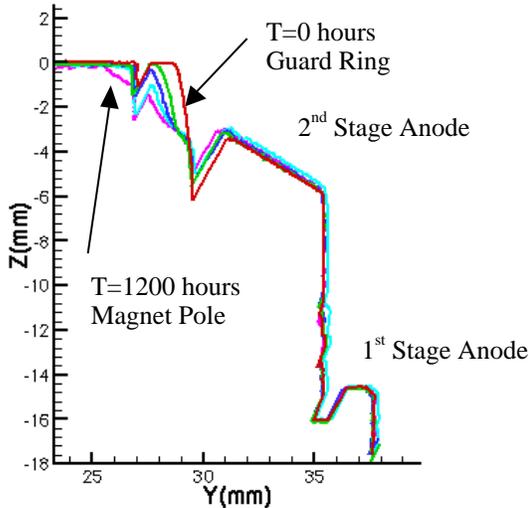


Figure 5 - D-80 Hall thruster high voltage erosion cross-sections.

Power Electronics

Discharge Power Module Development

Previous efforts to develop power electronics for Hall thruster systems were targeted for the 1 to 5 kW power range and output voltages of approximately 300 V. New Hall thrusters are being developed for higher power, higher specific impulse, and multi-mode operation. These thrusters require up to 50 kW of power and discharge voltage in excess of 600 V. SOA power processing units (PPUs) include a single converter as well as modular power architectures. Single converter designs are simple but their efficiency is largely reduced as the output and input voltage ranges increase. Also, for packaging considerations, these are only applicable to a few kilowatts. Modular designs can process more power with higher efficiency at the expense of added complexity. They also allow the use of redundant modules for higher PPU reliability.

A breadboard discharge power module capable of operating at 1 kW was designed, built and integrated with the NASA-120M Hall thruster. A printed circuit board (PCB), shown in Figure 6, was fabricated based on the design to facilitate fabrication of additional modules. These 300 V modules will then be used to build a high power discharge supply capable of operating the modules in either parallel for high current

operation or series for high voltage operation. This design will also be used as foundation for a multi-kW PPU for high power applications.

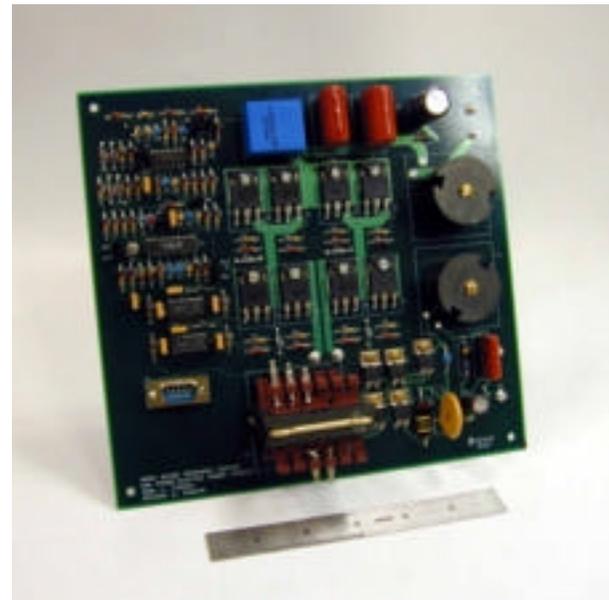


Figure 6 – NASA GRC's 1-kW discharge power module.

The discharge power module operates from an input voltage range of 80 to 120 V. Efficiencies in excess of 96 percent were measured, as shown in Figure 7. The mass of the PCB version of the power module is 0.765 kg. Piñero has a complete description of the development and testing.²⁶

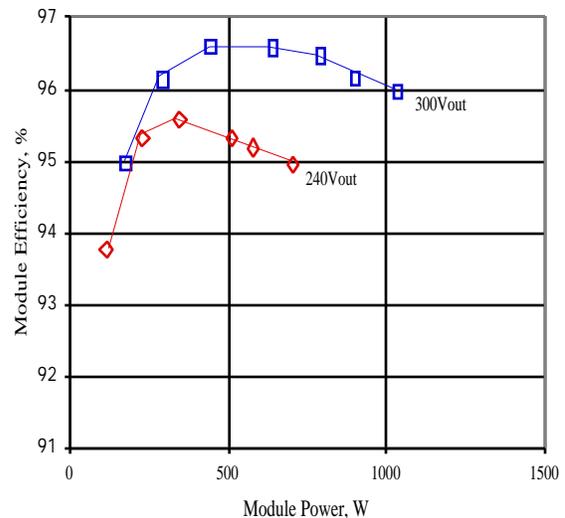


Figure 7 – Performance of the NASA 1-kW discharge power module

Hall Thruster Impedance Measurements

Hall thrusters exhibit discharge current oscillations in the 10^4 Hz range. A two-stage L-C output filter is traditionally used on the output of the discharge supply to protect it from these oscillations, which could induce instabilities and/or cause failure. If this filter is under-designed, it will not provide enough protection and over-designing could unnecessarily increase PPU mass. To design an optimum filter, it is necessary to have a clear understanding of the impedance of the plasma discharge in the thruster. An optimum discharge filter design provides impedance matching and stable operation between the thruster and the discharge supply under any operating condition. Understanding the electrical impedance of the plasma discharge can also help develop and validate electrical models of thrusters. Electrical models will enable new PPU architectures and trades to be made cost effectively

Impedance as a function of frequency can be measured using a frequency response analyzer. This instrument injects a calibrated sinusoidal signal into the thruster by means of a transformer. Then, it measures voltage and current at the thruster. The magnitude and angle of the impedance are calculated as the ratio of voltage and current and the amount of phase shift between them.

A measurement technique using a frequency response analyzer was tested and validated. Preliminary impedance data using a NASA Hall thruster (NASA-120M) is being studied. Additional testing on other thrusters is scheduled in the near future and results are planned for presentation at the International Electric Propulsion Conference in 2003.

Radio Frequency (RF) Phenomenon

It is well known that Hall thrusters exhibit dynamic electrical behavior in the form of discharge oscillation following start-ups, operating point changes, and even during otherwise "steady-state" operating regimes. Such behavior can have an impact on e.g., thruster life, power processor interface requirements, and communication signals transmitted through the thruster plume.²⁷⁻²⁹ Investigations of the root causes of such oscillations have revealed a variety of possible discharge instabilities, illuminating much about the physics of Hall discharges. What is less appreciated is that Hall thrusters also radiate erratic impulses of radio frequency (RF) emission during all phases of operation. These pulses became evident during MIL-STD-461 EMI measurement tests performed previously on both SPT-type and TAL-type thrusters.^{30,31} Collectively, the pulses cover a wide frequency range, extending to at least several GHz. Investigation of the RF pulse characteristics may provide insights into thruster discharge phenomena including anomalous electron

diffusion (near-wall conductivity), instabilities (e.g. electron stream type), plasma sheath transient behavior, and erosion state or rate. The potential of RF pulse emission measurement as a diagnostic method for such thruster phenomena has been suggested by observed correlation between larger RF pulses and discharge current oscillation mode/phase in previous NASA EMI tests (Figure 8). Also, Russian data on RF pulse emission acquired over a life test showed an increase in RF pulse emission intensity with erosion.³²

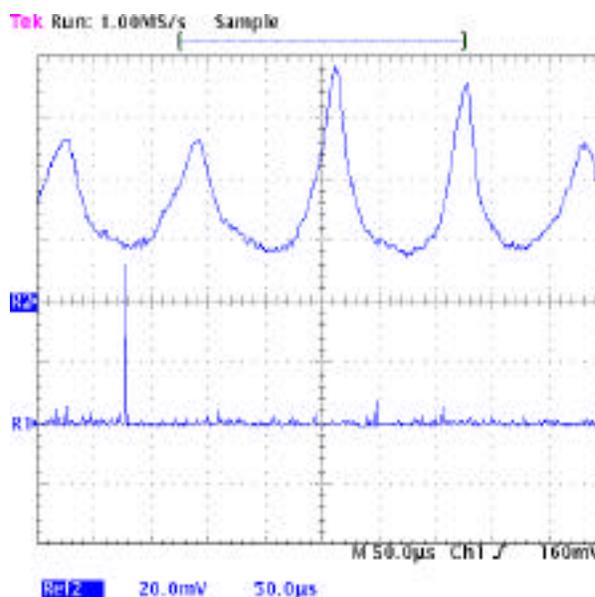


Figure 8 - Example of Hall thruster radiated RF pulse event correlating with discharge current oscillation minimum. R1 (lower trace): RF signal at 1.4 GHz as monitored by spectrum analyzer with 3 MHz bandwidth, scale linear in arbitrary units. R2 (upper trace): Discharge current, scale 10 Amps/div (5 Amps/10 mV).

Aside from being a diagnostic, the GHz content of the RF pulses makes them an important issue with regard to compatibility with spacecraft (S/C) communication bands. S/C receiver sensitivity to interference in such frequency bands is evident in S/C interface control document (ICD) requirements, which typically show deep notches in a generic EMI limits (e.g. MIL-461) at communication receive bands (Figure 9). Sub-5kW Hall thruster EMI data have indicated collective emission levels exceeding these notched limits. However, unlike random or thermal (i.e., Gaussian) type noise, the impulsive emission cannot be simply characterized by a RMS value. Its impact on a communication channel therefore cannot be evaluated without more detailed scrutiny than has been achieved in standard EMI tests. Development and application of higher power Hall thrusters or cluster architectures may further complicate

S/C integration unless the impulsive EMI emission is better understood.

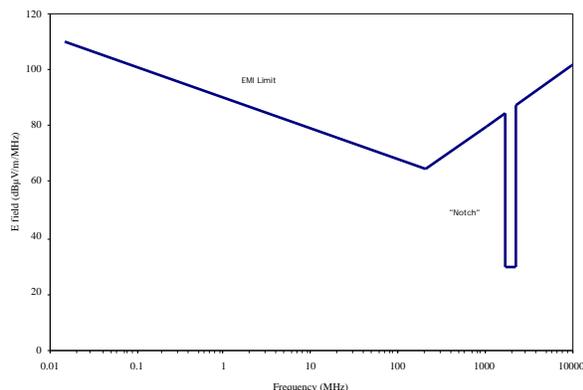


Figure 9 - Example of spacecraft broadband EMI limit specification with “notch” at communication receiving band.

The objective of this effort is to characterize the magnitude, frequency content, duration, and timing of individual RF pulses within a Hall thruster discharge.

Three methods are in the process of being applied to capture individual RF pulse characteristics and allow comparison to collective pulse data from EMI tests. First, a (tunable) single channel narrowband (~1 MHz bandwidth) receiver, as used for standard EMI tests, is being employed with a broadband antenna and low noise amplifier (LNA) to monitor radiated pulse intensity at a selected (GHz) frequency. A noise amplitude distribution (NAD) of impulse amplitude vs. rate will be measured for the selected frequency of interest. Secondly, a very wideband or time-domain capture of the sub-microsecond individual pulses is being performed with a LNA, diode detector, and fast digital storage oscilloscope (DSO). This should allow characterization of true pulse durations and/or shapes. This is not possible with more narrow bandpass detection as, e.g., with a 1 MHz resolution bandwidth spectrum analyzer in EMI tests or the first method mentioned above. With those methods, the pulses are stretched and distorted by the detector's input filter. Fourier analysis of un-rectified (i.e., diode detector removed) RF pulses is also being attempted for those with spectra falling within the Nyquist sampling limits of available DSOs. Combining the measurements of true pulse duration with NAD will provide a good foundation for analysis of the effects of such emissions on communication channels of various bandwidths or modulation schemes.

Finally, to better understand the NAD for a fixed frequency band and the possible mechanisms for RF pulse generation by the Hall discharge, a multi-channel detection scheme is being employed in an attempt to determine the carrier frequency content and its

variability from pulse-to-pulse. That is, the fluctuating spectra of individual pulses will be captured and compared to the collective or envelope spectrum acquired by sweeping a single channel detector across a wide frequency range during many such pulses, as done in conventional EMI measurements. It is expected that an individual pulse spectrum will have much less frequency extent than the several GHz wide spectrum suggested by previous EMI test results.

This effort will provide an important baseline for analysis and modeling of Hall thruster phenomenon. Specifically, data on Hall thruster RF impulsive emission on a communication channel and for thruster design/operating point effects on such emission. This type of data will help provide insight into the fundamental processes taking place within Hall thrusters and possibly how to design to a given EMI specification.

The NAD for RF pulse emission at a particular GHz frequency will be determined as best as signal to instrument noise allows. Actual duration and frequency spread of individual RF pulses will likely be found to be shorter and narrower, respectively, than previously thought. Pulse-to-pulse frequency hopping in addition to pulse energy variations will therefore affect the NAD for a given GHz frequency. It is expected that the NAD will shift and possibly also change shape as the thruster changes operating mode or erodes significantly. It is expected that the NAD should be reproducible from one run to the next for the same operating point once the thruster stabilizes. Different thruster types or designs may be associated with different NADs for similar operating conditions. Future tests could explore this aspect if the measurement approach proves feasible.

Once the measurement methods have been established, the effects of thruster design and operating condition on RF pulse intensity (amplitude and rate) can be investigated to probe the possible mechanisms of pulse generation and weigh the integration risks of new thruster developments. Some examples of interest include:

1. Effect of insulator wall material (e.g. secondary electron emission) on RF pulses
2. Effect of thruster operating voltage on RF pulse intensity
3. Effect of thruster magnetic field on RF pulse intensity
4. Effect of thruster scale (power or cluster #) on RF pulse intensity
5. Effect of SPT vs. TAL acceleration geometry on RF pulse intensity
6. Effect of single vs. two-stage operation on RF pulse intensity

7. Variation of RF pulse intensity vs. thruster life/erosion state
8. Correlation of RF pulses with signals from invasive electrical probes in discharge

Summary

The NASA Hall thruster program currently supports tasks for a number of customers including the Energetics Program, the Space Solar Power Program, and the In-space Propulsion Program. In program year 2002 the following was accomplished as part of these tasks: 1) A laboratory Hall thruster was built and tested to 72 kW and 3 N of thrust; 2) A 5.5% increase in thruster efficiency at high voltage was demonstrated by modifying the magnetic field profile; 3) High voltage Hall thruster lifetime was quantified; 4) A 96.5% efficient breadboard power module was demonstrated; 5) A technique for measuring the impedance of a Hall thruster was demonstrated; and 6) A plan for investigating the dynamic electrical behavior of Hall thrusters was presented.

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