Ion Propulsion Development Activities at the NASA Glenn Research Center[*†]

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The NASA Glenn Research Center (GRC) ion propulsion program addresses the need for high specific impulse ion propulsion systems and technology across a broad range of mission applications and power levels. Development areas include high-throughput NSTAR derivative engine and power processing technology, lightweight high-efficiency sub-kilowatt ion propulsion, micro-ion propulsion concepts, engine and component technologies for high-power (30 kW class) ion engines, and fundamentals. NASA GRC is also involved in two highly focussed activities: development of 5/10-kW class next-generation ion propulsion system technology, and development of high-specific impulse (> 10,000 seconds) ion propulsion technology applicable to deep-space and interstellar-precursor missions.

Introduction

With the success of the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) program ion propulsion system on the Deep Space One spacecraft,[1] the future for this propulsion technology for other NASA missions, and missions of national interest, appears promising. Several missions under consideration for the exploration of the solar system have identified ion propulsion as an enabling technology. These missions include the Europa Lander, the Saturn Ring Observer, the Neptune Orbiter, and the Venus Surface Sample Return.[2]

Additionally, a general need for high specific impulse (> 1000 sec), low-power (~10 W) propulsion has also been identified for second

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generation Jet Propulsion Laboratory (JPL) microspacecraft,[3] and there is the potential for micro-ion propulsion concepts to play a role. Also, a krypton ion propulsion system has been selected as the back-up propulsion option for the Interstellar Probe Mission (IPM), presently scheduled as a new-start in 2007.[4] The requirements for the ion propulsion system include 100 kW input power, a 10-year engine life requirement, and a specific impulse in the range of 10,000-15,000 seconds.[5]

The NASA Glenn Research Center (GRC) is pursuing technology development in ion propulsion for a range of mission applications, including the aforementioned opportunities. Support for these efforts is provided by both the Space Base (NASA's Cross-Enterprise Technology Development Program), and the In-Space (NASA's Advanced Space Transportation Program) elements.

The Space Base program at NASA GRC includes a broad range of activities in the following areas:

- Development of high-power (~30-kW class) ion engine and component technologies applicable to HEDS-class missions;
- Development of engine component technologies for NSTAR-derivative high-throughput ion engines, and high-power power processor units;
- Development of lightweight sub-kilowatt ion propulsion system technology;
- Feasibility assessments of micro ion propulsion concepts; and
- Fundamentals – development of advanced diagnostics for life assessments, quantification of erosion processes, and development of new cathode technologies.

Two focussed technology development activities are pursued under the In Space program, and these include:

- Development of the next-generation ion propulsion system as follow-on to the Deep Space One system, utilizing a 10 kW ion engine; and
- Development of 10-30 kW class high specific impulse (> 10,000 seconds) ion propulsion, applicable for interstellar precursor missions.

Development work in these areas is implemented by a combination of in-house activities, contracts with U.S. industry, and grants with universities. The in-house ion propulsion activity takes advantage of the NASA GRC resident expertise and unique electric propulsion infrastructure which has been established over the past 40 years. In-house activities include: design, manufacturing, test and evaluation of advanced (non-carbon-based) ion optics, laboratory and engineering model ion thrusters, breadboard power processing units, and component technologies for high-power ion and Hall engines; development and testing of micro-ion engine concepts; and fundamentals work in diagnostics, low-energy sputtering, and cathodes. These activities establish design requirements and specifications that can then be transferred to U.S. industry for flight application.

Industry participants and their associated activities in the NASA ion propulsion program include:

- *Boeing Electron Dynamic Devices* (formerly *Hughes*) – development of 5 kW power processor technology;
- *Ceramic Composites, Inc.* – manufacturing of carbon-carbon ion optics;
- *General Dynamics* (formerly *Primex Aerospace Company*) – development of sub-kilowatt ion propulsion system technology;

University participants and their associated activities in the NASA ion propulsion program include:

- *Colorado State University* – use of ion-implantation to reduce the sputter yield of ion optics materials for high-power ion thrusters, and modeling and experimental evaluations of high-voltage ion optics;
- *University of Michigan* – development of advanced life diagnostics to assess engine wear, and development of a numerical model to predict ion optics lifetime and performance.
- *North Carolina A&T State University* - manufacturing of carbon-carbon ion optics;
- *Ohio Aerospace Institute* – development of advanced life diagnostics tools and implementation at GRC;
- *Tuskegee University* – modeling of low-energy sputter yield processes in refractory metals; and
- *Whitworth College* – development of Laser

Induced Fluorescence (LIF) of carbon and carbon-clusters.

Partnerships and collaborative activities are also conducted with the following organizations:

- *Wright-Patterson Air Force Base* - technical assistance in management of carbon grid development contracts, funded under the Air Force materials program;
- *Environmental Molecular Sciences Laboratory/Pacific Northwest National Laboratory* – Rutherford Backscattering Spectrometry of materials samples generated at NASA, for evaluation of sputter yields; and
- *JPL* – A variety of joint efforts are conducted, including experimental assessments performed at GRC on cathode erosion in the NSTAR engine, and mechanical design and test support of a JPL-led effort for the development of carbon-carbon ion optics for high specific impulse ion propulsion.

Figure 1 synopsizes the activities in the NASA ion propulsion program. This paper discusses the technology goals and products associated with the Space Base technology program, and the In Space focussed development activities. Near-term milestones, and progress against these milestones, are delineated.

Space Base Activities

This section describes the activities conducted under the Space-Base program, examining a variety of technologies for future mission opportunities.

High-Power Engine and Component Technologies

The long-range goal of this activity is to develop and demonstrate ion engine operation at 30 kW input power levels and above, at specific impulse levels of interest to support human exploration of the solar system. A near term objective is the demonstration of ion engine operation in the range of 10-30 kW, at 4000 seconds specific impulse.

For high-power operation, one engineering approach to circumvent the difficulties normally encountered with large span-to-gap ion optics is to use multiple ion optics sets of a proven design and of smaller diameter and span-to-gap, to extract the ion current from a common discharge chamber.[5,6] For missions requiring 4000 second specific impulse operation, this approach potentially provides an avenue for rapid near-term high-power ion engine development.

As part of this activity, development work in high-current hollow cathodes was initiated at NASA GRC. This included the design and fabrication of high-current hollow cathode assemblies.[7,8] A preliminary 100-A class cathode is shown in Figure 2; it operated stably over a range of emission currents from about 14 A to 100 A on xenon propellant, although thermal-redesign is required to yield adequate life time at >50 Amperes emission current.

NSTAR-derivative Technologies

The activities under this element are focussed on development of component technologies for NSTAR-derivative high-throughput ion engines, and advanced power processing technology.

Ion Optics

The primary objective of this effort is to develop and validate ion optics designs which yield a > 2x increase in life over that demonstrated with the Deep Space One ion engine optics technology. This includes efforts in both metallic (molybdenum and titanium) as well as carbon-based (carbon-carbon, and pyrolytic graphite) ion optics designs.

In the metallic optics work, evaluations of both thick-accelerator-grid (TAG) electrode molybdenum designs, and titanium designs are underway. TAG molybdenum ion optics of 30 cm diameter have been manufactured in-house and characterized over, and beyond, the Deep Space One power throttling envelope.[9] The TAG ion optics utilize a 50% thicker accelerator grid (relative to the Deep Space One design) in an attempt to double the optics service life. Results from these tests are extremely encouraging, with the TAG design having demonstrated comparable perveance to that obtained with flight ion optics for the NSTAR Deep Space One engine (Figure 3).[9] After completion of refinements in the manufacturing process associated with aperture placement, a long-duration wear test of the TAG optics is anticipated to demonstrate the increase in service life.

Titanium ion optics of 30 cm diameter have also been manufactured and performance characterized.[10] The potential advantages of titanium, over molybdenum, include a lower volumetric sputter erosion rate, reduced cost of manufacturing, and reduced optics assembly mass. As seen in Figure 3, the performance of these optics compare favorably to those of the NSTAR design as well. Additional work to be performed includes detailed evaluations of the transient electrode gap change of titanium optics under thermal load.

One way of improving metallic grid lifetime involves ion implantation as a final step of grid fabrication.[11] Molybdenum and titanium grid materials were implanted with nitrogen or carbon at a high current density and at an elevated temperature. Such treatment enables diffusion of the implanted species substantially beyond their ballistic implantation depths and facilitates treatment to required depths at a reasonable cost. The processing is most cost effective at the highest possible implantation temperature where diffusion rates are greatest, and for both Mo and Ti this is about 850 C. Beyond this temperature a phase change induces unacceptable warpage in Ti and recrystallization induces unacceptable brittleness in Mo. In order to effect treatment of most of the grid thickness and also to prevent grid warpage it appears that both sides of a grid would have to be implanted simultaneously. Results suggest that a 50% reduction in the sputter yield of Ti can be accomplished by implanting it with C. A lesser reduction in yield (~30%) is observed when N is implanted into Ti and when C is implanted into Mo. The smallest reduction is observed when N is implanted into Mo (~15%).

Carbon-based ion optics are also under design and manufacturing, with activities including fabrication of carbon/carbon composite grids using multiple vendors with alternate processes, and fabrication of pyrolytic graphite grids of 8 cm (Figure 4) and 30 cm diameter from a commercial supplier.[12] Carbon has key material properties which exceed those of molybdenum. Graphite carbon has a very low coefficient of thermal expansion that is nearly zero in some situations. This is important in order to maintain precise geometric alignment between screen and accelerator aperture holes. High performance ion thrusters typically have large grid span-to-gap ratios which are vulnerable to thermal distortion. The high geometric stability of carbon materials may permit larger diameter thruster designs while still maintaining high beam density. Alternately, it may be possible to significantly increase the beam density of low power ion thrusters, improving applications on small spacecraft.

The sputter erosion rate of graphite is much lower than any known metal. At some energy levels, it has been shown to have erosion rates an order of magnitude less than that of molybdenum. The use of carbon ion optics could drastically increase the life of ion thrusters by reducing electrode erosion that ultimately leads to structural failure. Carbon fiber is a very stiff material. It has an elastic modulus higher than that of most metals, but with a mass density lower than most metals. Components fabricated of carbon/carbon composites typically have very high natural resonant frequencies, and are more robust in high vibration launch vehicle environments. High material stiffness is also important to minimize ion optics distortion due to high voltage electrostatic attraction. Ion optics could be designed as flat panels in some situations, reducing fabrication cost, while maintaining aggressive span-to-gap proportions.

Additional ion optics activities conducted in-house involve advanced concepts: grid-translation thrust-vectoring, application of magnetic fields to inhibit electron backstreaming, and high-voltage ion optics operation. The evaluation of a grid-translation technique for engine thrust vectoring[13] involved testing a 30 cm diameter ion engine in which the accelerator grid of high-perveance ion optics (of the Deep Space One design) was translated with respect to the screen grid in the radial plane. The engine was operated at different throttle power levels, and the accelerator grid was incrementally translated in the X, Y, and azimuthal directions. Results show that the engine plume can be deflected up to 6 degrees without a prohibitive increase in accelerator impingement current.[13]

A novel approach to inhibit electron backstreaming, by the application of transverse magnetic field was also investigated.[14] Electron backstreaming due to accelerator grid hole enlargement has been identified as a failure mode. Over time as accelerator grid apertures enlarge due to erosion, ion thrusters are required to operate at increasingly negative accelerator grid voltages in order to prevent electron backstreaming. These voltages give rise to higher grid erosion rates, which in turn accelerate the accelerator grid structural failure. The effect of a transverse magnetic field imposed on the downstream side of the accelerator grid on electron backstreaming was studied. Data indicates that the imposed magnetic field reduces magnitude of backflowing electron current. The reductions in current are consistent with classical transverse diffusion. Additionally, the electron backstreaming limit was found to decrease linearly with increasing magnetic field strength. The data suggests that the transverse magnetic field approach may be used to add engineering margin to a thruster.

Electric propulsion mission analyses have always shown significant benefits of increasing the power per thruster and hence reducing the required numbers of thrusters and power processors. Implicit in many of these analyses is the assumption of constant lifetime. For near-term missions with optimum values of specific impulse in the 3000-4000 second range, the power increase is accomplished by increasing the average ion beam current density to as much as 8 mA/cm^2. However, previous tests usually ended with unexpected internal and external erosion mechanisms, and unacceptably high erosion rates. The concept of a "derated" ion thruster evolved from these early tests. The success of NSTAR's ground test program and its transition to a record-setting flight on Deep Space One was a direct result of the concept of “derating.” The maximum value of NSTAR's average ion beam current density is about 2.7 mA/cm^2.

Another way to increase the power per thruster is to raise the exhaust velocity via an increase in the ion beam's net accelerating voltage. A 35 percent increase in input power, without increasing the beam current density, was recommended for the proposed Comet Nucleus Sample Return and has been demonstrated using a 30-cm diameter thruster nearly identical to the NSTAR flight thruster.

In attempts to further increase the power per thruster in this manner, greater increases in the net accelerating voltage result in excessive electrical breakdowns in the grid active area. Also the magnitude of the accelerator grid voltage must increase to prevent beam electrons from backstreaming into the discharge chamber. Therefore, the grid-to-grid spacing must be increased. An experimental evaluation of grid-to-grid spacing and its impact on ion beam extraction, electrical breakdowns, electron backstreaming, and range of power throttling was conducted using a 30 cm engineering model thruster and are reported in detail elsewhere.[15]

Cathode Lifetime

The requirements on hollow cathode life are growing more stringent with the increasing use of electric propulsion technology and demand for longer total impulse capability. The life limiting mechanism that determines the entitlement lifetime of a barium impregnated thermionic emission cathode is the evolution and transport of barium away from the emitter surface. In concert with a robust hardware development effort at NASA GRC,[7,16] a model is being developed to study the process of barium transport and loss from the emitter insert in hollow cathodes.[17]

The coupled thermochemistry/diffusion model has been developed for xenon hollow cathode operation and it shows good qualitative agreement with observable phenomena in hollow cathodes. The model has been used initially to examine the evolution and loss of Ba from the insert impregnate. Model results have also been compared to qualitative experimental evidence of chemical processes within the cathode insert.

Flake Retention

Grit-blasted wire mesh on stainless steel backing is commonly used in ion engine discharge chambers to ensure adherence of sputtered coatings. Spalled coatings or flakes pose some risk in shorting the high-voltage ion optics. If spalling does occur, the fine wire mesh ensures the spalled material will have sufficiently small dimensions so electrode gaps can not be bridged. A 8,200 hour ground test of a 2.3 kW ion engine had no problems that could be attributed to spalled flakes.[1] This test had a xenon throughput of 88 kg. Post-test analyses indicated the coatings and flakes were primarily molybdenum and were in the 2 μm to 12 μm thickness range. The Deep Space One ion engine has operated in zero-g conditions for over 11,000 hours, and no problems have been encountered due to spalling of the chamber coatings.

Next generation ion engines will likely have xenon throughput requirements in the 200 kg to 550 kg range, implying longer operation, higher power levels, and thicker sputtered coatings internal to the engine. An activity was therefore initiated to establish the limits of the retention of sputtered molybdenum on ion engine discharge chamber surfaces.[18] On-going testing involves the application of thick molybdenum coatings (up to 130 μm) to grit-blasted aluminum, titanium, and wire mesh, all candidates for discharge chamber material. The coupons are then subjected to thermal cycling tests and subsequent visual inspections and mass measurements to evaluate film adherence.

Power Processing

A 5 kW breadboard ion power processing unit (PPU) is being designed and fabricated under contract with Boeing Electron Dynamics Devices. The desired result is a PPU design that can be expected to operate at 5 kW and high efficiency (greater than 92%), while yielding a low mass (15 kg flight-packaged PPU, less cabling); a 2x reduction in specific mass compared to the Deep Space One power processor. The products of the first-year design study include top-level drawings of the breadboard PPU, detailed design schematics for the breadboard beam supply, and a breadboard beam supply.

The PPU design includes a beam supply consisting of four 1.1 kW power modules connected in parallel and equally sharing the output current.[19] A novel phase-shifted/pulse-width-modulated dual full-bridge topology was chosen for its soft-switching characteristics. The modular approach allows scalability to higher powers as well as the possibility of an N+1 redundant beam supply.

A 1.1 kW beam supply module has been designed and fabricated. A phase-shift/pulse-width modulated dual-bridge topology operating at a switching frequency of 50 kHz was selected for this design. Beam power supply efficiencies ranging between 92 to 96 percent were measured for an input voltage range of 80 to 160 V and an output voltage range of 800 to 1500 V for powers from 300 to 1100 W.[19] This beam supply could result in a PPU with a total efficiency of up to 94.5 percent, which is up to 2 percent improvement over the Deep Space One PPU.

Additional work will include design and fabrication of the breadboard discharge, neutralizer keeper, accelerator and heater supplies and integrating them with the beam supply into a complete breadboard PPU. Then the breadboard PPU will be integrated with a 40 cm diameter ion engine at NASA.

Sub-kilowatt Ion Propulsion

The goal of this activity is to develop lightweight (< 3.0 kg combined mass), sub-kilowatt thruster and power processor technology. Performance goals include 50% efficiency at 0.25 kW, representing a 2x increase over state-of-the-art.

The sub-kilowatt ion propulsion activity includes both an in-house hardware development element for the thruster and power processor, as well as a contracted system element. At NASA GRC, the fabrication and performance assessment of a small (0.25 kW class) laboratory model thruster with an 8 cm beam diameter has been completed,[20-23] and the fabrication of a second-generation light-weight engineering model thruster with a 100-500 W power throttling envelope has also been completed. Also at NASA GRC, first- and second-generation breadboard power processors have fabricated and successfully integrated with the 8 cm thruster.[24-26]

The second-generation breadboard PPU (Figure 5) was fabricated with a maximum output power capability of up to 0.45 kW at a total efficiency of up to 90 percent. Four power converters were used to produce the required six electrical outputs which resulted in large mass reduction for the PPU. The component mass of this breadboard is 0.65 kg and the total mass is 1.9 kg. Integration tests with the thruster included short circuit survivability, single and continuous recycle sequencing, and beam current closed-loop regulation.

General Dynamics, under contract, developed a conceptual design for the low power ion propulsion system. The objectives of this effort were to develop a system that improved performance and reduced system mass compared to existing state of the art systems. The resulting design was tailored to the meet the needs of the satellite and spacecraft integration community as identified in an extensive user survey performed by General Dynamics. The conceptual design for the low power ion propulsion system is shown in Figure 6.[27] The basic characteristics of the system are as follows:

- up to 20 mNewtons thrust
- 100-500 Watts input power
- 1600-3500+ seconds Isp
- thruster mass: 0.95 kg
- PPU mass: 2.0 kg
- Xenon Feed System mass: 3.1 kg (excluding tank)

Micro-Ion Propulsion

An in-house research activity is being conducted to evaluate the feasibility of various micro ion propulsion concepts. The goal is to develop an engine with >25% efficient, >1500 seconds specific impulse, at <50 W input power. One such concept under investigation is the a micro ion thruster based on low-power hollow cathode technology, referred to as the Hollow Cathode Micro Thruster (HCMT).[28]

The HCMT provides thrust by accelerating ions produced by a miniature hollow cathode utilizing a high-voltage acceleration stage. The proposed thruster overcomes the technological roadblocks that prevent scaling down conventional ion engines and Hall-Effect Thrusters because the ionization process eliminates the issues of neutral loss and magnetic confinement.

The hollow cathode of the HCMT is based on 3.2 mm diameter technology, and incorporates design features to maximize its ion production. In preliminary tests of the hollow cathode, ionization efficiencies in excess of 50% were measured. Subsequent testing of the HCMT incorporating the hollow cathode were conducted with beam extraction (Figure 7), at accelerating potentials up to 1500 eV using a 2-electrode ion optics configuration. The electrical and propellant efficiencies of the hollow cathode are sufficient to achieve the performance goals for beam voltages in excess of 2000 V. However design modifications to the ion optics will be required to improve the ion transparency.[28]

An alternative micro ion engine concept under investigation is the Compact Plasma Accelerator, or CPA.[29] In this work, the feasibility of utilizing a magnetic cusp to generate a dense plasma over small length scales is investigated. This approach could potentially mitigate the need for large containment volumes (size) in order to achieve reasonable ionization efficiencies. The discharge plasma is both generated and accelerated via this approach using, in principle only a single power supply.

The CPA demonstrated the capability of generating ion beamlets (~80 eV) of current densities comparable to that of higher power devices. In general, the device appeared to operate best at very low flow rates. Under these conditions, the ion production as well as ion energies appear to be highest. The CPA as configured shows promise as a stand-alone plasma accelerator for propulsion or as a low energy ion source that could be used for plasma/materials processing applications.

Fundamentals

This activity is focussed on enabling high-quality lifetime assessments of high-thrust density ion propulsion via development of advanced diagnostics and understanding of erosion processes. It involves both in-house efforts, as well as those performed by University of Michigan, Tuskegee University, the Ohio Aerospace Institute (OAI), and Whitworth College. Activities for the development of propellant-less cathode technology are also under investigation, and discussed below.

Diagnostics and Life Modeling

The over-arching goal of this effort is to develop in-situ diagnostic capabilities to rapidly assess engine life. To this end, a number of near-term goals have been established for diagnostics development, and these include:

- Demonstration of laser induced fluorescence (LIF) diagnostic to measure the density of erosion products from Mo components (NASA GRC);
- Quantification of engine internal and external Xe velocity and density measurements (OAI, at NASA GRC);
- Demonstration of LIF of C and detection of C-clusters from sputter eroded graphite (Whitworth College); and

- Completion of internal probe based diagnostics of the discharge plasma in a 30 cm xenon ion engine (University of Michigan).

Several activities have been recently conducted at NASA GRC to both develop and utilize these diagnostic techniques. Laser induced fluorescence measurement of molybdenum number density is being developed to evaluate the erosion of molybdenum engine components.[30] A calibration technique to yield absolute erosion rates has been established. A molybdenum tube was resistively heated such that the evaporation rate yielded densities within the tube on the order of those expected from accelerator grid erosion, and a model has been developed to describe the vapor density distribution within the tube.[31]

Tests were also conducted at NASA GRC to identify the cause of excessive discharge cathode keeper erosion in the on-going Extended Life Test (ELT) of the NSTAR flight spare thruster being conducted at JPL.[32] . In order to identify the cause of the erosion, emission spectra from an engineering model thruster were collected to assess the dependence of keeper erosion on operating conditions, and keeper ion current was measured to estimate wear. The analysis indicated that the bulk of the ion current was collected within 2-mm radially of the orifice, and the greatest wear condition was identified to be at the NSTAR maximum throttling condition. Estimates of the volumetric keeper erosion in the ELT appear to overlap the results of the previous 8,200 hour wear test. However the ELT keeper erosion is distributed differently, likely due to a different spatial distribution of ion current to the keeper.

The investigation of cathode keeper erosion is also being supported by work at the University of Michigan under NASA GRC grant. Relative erosion rates of the cathode and keeper orifice plates have been made via LIF in a 30 cm ion thruster over the engine's nominal throttling range.[33] The investigation included extensive LIF ion velocity measurements, as well as ion and neutral density measurements made near the exit plane of the cathode.

Low-Energy Sputtering

The objective of this activity is to develop a fundamental understanding of low energy sputtering processes, and to measure low energy sputtering yields of materials relevant to ion thrusters. This activity is being conducted jointly with Tuskegee University. A long range goal is to quantify the sputter yields of relevant refractory metals under ion bombardment, down to the threshold energies. A near-term goal is the quantification of the sputter yields of Ta, Ti, and Mo under Xe ion bombardment down to 100 eV.

To date, low energy (< 500 eV) xenon ion sputtering yields were measured of molybdenum and tantalum targets.[34] The sputtering was carried out in an ultra high vacuum chamber at NASA GRC. The targets were bombarded with a xenon ion beam generated by an ion gun capable of producing a beam current of approximately 1 μA. The sputtered atoms were captured on a semi-cylindrical aluminum collector strip, which was subsequently removed from the vacuum chamber and analyzed with a Rutherford Backscattering Spectrometer. The sputter yield was then obtained from the atomic density and thickness of the sputtered film.

At Tuskegee University, a study has been initiated to investigate interactions between low-energy xenon ions and molybdenum using molecular dynamics (MD) simulation.[35] An MD code designed for simulations of atomic collisions in solid lattices is used in this study. This code solves Newton's equation of motion numerically with forces derived from potential functions. The ion energies used range from 100 to 500 eV. A description of the MD code used and sputtering yields obtained through this simulation can be found in Reference 35.

Cathode High Energy Ion Formation

The production of energetic ions in a hollow cathode discharge is well documented.[36-39] These energetic ions have been detected at energies well in excess of the discharge voltage. Energetic ions are capable of eroding not only ion thruster cathode and keeper electrodes, but also discharge chamber surfaces such as the screen grid. Such erosion processes can lead to thruster performance degradation and ultimately engine failure. In this regard, cathode production of energetic ions may be a thruster life-limiter particularly for long duration missions. The mechanism behind the production of these energetic ions is still unresolved.[39] Proposed mechanisms include multiply-charged ion processes, potential hills, charge-transfer effects, and z-pinch acceleration.[39,40] Though the theories explain the generation of energetic ions given the presence of certain mechanisms, compelling experimental evidence to support any of the theories remains elusive.

In order to address and better understand this issue, an experimental investigation of the formation of high energy ions in high-current hollow cathodes has been initiated at NASA GRC. The goal of this investigation is to characterize the energy distribution and estimate the magnitude of the energetic component of the emitted ions generated by a high current hollow cathode. These measurements will be made using a high fidelity low energy analyzer and Langmuir probe diagnostics. The data obtained will be used to develop a model that describes the production of the energetic ions as a function of operating condition.

Propellantless Cathode Technology

The goal of this activity is to develop a propellantless cathode technology appropriate for electric propulsion applications. Low-power electric thrusters, spacecraft plasma contactors, and electrodynamic tether systems need electron emitters that require very low gas flow rates or zero gas flow to perform their functions. In order to ensure that very low-power colloid thrusters, Field Emission Electric Propulsion devices, ion engines, Hall thrusters, and gridded vacuum arc thrusters are reasonably attractive systems, a propellantless neutralizer cathode is highly desirable.

To this end, two cathode concepts are under investigation at NASA GRC including field emitter array (FEA) cathodes, and cathodes based on pulsed ferroelectric ceramics. Much of the work to date with FEAs has dealt with developing silicon or molybdenum tip cathodes. Reference 41 reports on work focusing on comparing the electrical performance of other candidate FEA cathode materials including plasma-processed diamond, carbon nanotubes, diamond-like carbon, and textured metals. Goals for this series of experiments include obtaining current densities greater than 10 mA/cm^2 with electric fields less than 25 V/μm. Short-term evaluations of FEA cathodes were conducted at a xenon background pressure of about 1 x 10^{-6} Torr to assess emission current stability in such an environment, and test results of the various FEA cathode materials in simple diode arrangement were summarized.

An experimental effort on ferroelectric emission cathodes has also being initiated at NASA GRC.[41] Ferroelectric emission (FEE) refers to the pulsed emission of electrons from ferroelectric ceramic materials. Ferroelectrics are ceramics with a spontaneous electric polarization. Electron emission of up to 100's of A/cm^2 be obtained by applying fast rise time, high voltage pulses to the ferroelectric such that the polarization reverses (requiring a bipolar pulse) or partially reverses (requiring a unipolar pulse).

In Space Activities

This section describes the two focussed development activities which are being conducted under the In-Space program.

5/10-kW Next Generation Ion Propulsion

One focussed activity is the development of the next-generation ion propulsion system as follow-on to the highly-successful Deep Space One system.[42,43] This advanced propulsion system is envisioned to incorporate a lightweight ion engine capable of operating over a 1-10 kW power throttling range with a 550 kg propellant throughput capacity. The engine concept under development has a 40 cm beam diameter, twice the effective area of the Deep Space One engine, while maintaining a relatively-small volume. It incorporates mechanical features and operating conditions to maximize the design heritage established by the flight NSTAR 30 cm engine, while incorporating new technology where warranted to extend the power and throughput capability.

Specific goals for this next-generation ion propulsion system include:

- 1.0-10 kW engine power throttling range appropriate for both Earth-orbit applications of national interest, and primary propulsion for deep-space interplanetary missions (4x increase in input power and 2.5x increase in throttling range over the NSTAR propulsion system);

- 550 kg engine throughput capability delivering a total impulse of 2.1×10^7 N-s (6x increase over the NSTAR thruster);
- 12 kg thruster mass with mechanical design envelope comparable to the NSTAR thruster, and a 92% efficient, 27 kg power processor mass (3x and 2x reduction in specific mass for the thruster and power processor respectively compared to NSTAR); and
- a flight system cost target of 1/2-NSTAR recurring cost.

Fabrication of two prototype 40 cm engines has been completed, and detailed performance characterizations of both designs are on-going at NASA GRC.[42,43] The two engines vary in discharge chamber geometry and magnetic circuit design. Figure 8 shows the thruster efficiency as a function of input power for one of the engines. Typical performance at 7.3 kW input power is 68% efficiency, 3615 seconds specific impulse, and 280 mN thrust. Figure 9 shows the engine in operation. Engineering model (EM) engine designs, based on the two prototype concepts, have been completed. Manufacturing and assembly of the EM engines has been initiated, including the 40 cm diameter ion optics.[44]

Under this program, a numerical model is being developed through a grant with the University of Michigan to predict the lifetime and performance of the ion thruster's ion optics. An existing, validated computational model for ion flow in an ion thruster accelerator system was initially developed to predict the performance of ion thruster optics.[45] The computational model is a two-dimensional code that combines two modeling methods. In the first method, a hybrid-fluid Particle-In-Cell technique is used to model the plasma dynamics, where both singly- and doubly-charged ions are considered. Electrons are assumed to exist only upstream and downstream of the ion optics. In the second method, a Direct Simulation Monte Carlo technique is used to model collision phenomena. These collisions include not only the charged particles, but also neutrals. The types of collisions modeled include charge-exchange, momentum transfer, and Coulomb collisions. This model is being enhanced to determine accelerator grid sputter erosion by charge-exchange ions and predict the onset of electron backstreaming.[46] Verification of the model is provided by applying results to the Deep Space One thruster, which has been extensively tested and documented.

Interstellar Ion Propulsion

NASA has been tasked to develop technologies to enable exploration of interstellar space in support of the Interstellar Probe project, and other missions. One of the key technical challenges is the development of the nuclear electric propulsion system, for which NASA GRC is responsible for developing the ion propulsion system. It is the goal of this long-range activity to develop a high specific impulse (>10,000 seconds), 10-30 kW krypton ion engine in support of these missions.

The activities initiated at NASA GRC are in the second-year of a multi-year effort involved in development of this high specific impulse ion engine. In the first-year, the objective was to fabricate and test an engine discharge chamber. A test-bed engine was designed and fabricated, with a nominal discharge chamber diameter of 76 cm. Preliminary discharge chamber performance data were obtained on both krypton and xenon propellants over a range of conditions, including electron and ion current measurements obtained from an array of internal discharge chamber diagnostics.[5]

This year, the objective is to design, manufacture, and test large-area ion optics and demonstrate operation at > 10,000 seconds specific impulse. A 2-dimensional electrostatics computer code was exercised and prior ion optics studies were reviewed to determine preliminary designs.[47,48] Several sub-scale sets of ion extraction grids were then fabricated and tested at NASA GRC and at Colorado State University. Testing was performed using krypton propellant at values of beam current density and exhaust velocity anticipated for 30 kW operation, including operation at voltages corresponding to 14,000 seconds specific impulse (see Figures 10 and 11). Based on the performance of the discharge chamber and the sub-scale grids, full-scale grids have been designed, and are presently under fabrication.

One major finding of the design phase was that at the large grid-to-grid spacing required to maintain a reasonable electric field, the magnitude of the accelerator grid voltage could be less than 500 volts; much lower than the 2-3 kV anticipated from scaling standard ion optics. Another finding was that if the maximum beam current density was held to a value about 40% that of the Deep Space One engine then use of molybdenum or titanium for the grid material is sufficient to achieve the required 10-year lifetime. Thus, advanced, low sputter yield carbon-carbon materials are not required.

Summary

The NASA Glenn Research Center ion propulsion program addresses the need for high specific impulse ion propulsion systems and technology across a broad range of mission applications and power levels. The ion propulsion program includes a Space Base effort covering a broad range of activities, and two focussed technology development activities under the In Space Advanced Space Transportation Program.

The Space Base ion program includes development of engine component technologies for NSTAR-derivative high-throughput ion engines, and high-power power processor units. The engine work is primarily focussed on developing and validating ion optics designs which yield a > 2x increase in life over that demonstrated with the Deep Space One ion engine optics technology. This includes efforts in both metallic as well as carbon-based designs. The PPU activity involves development of 5 kW, high efficiency design, yielding a mass of about 15 kg; a 2x reduction in specific mass compared to the Deep Space One power processor.

Additionally, the Space Base effort includes: development of lightweight sub-kilowatt ion propulsion system technology; feasibility assessments of micro ion propulsion concepts; development of high-power (~30-kW class) ion engine and component technologies applicable to HEDS-class missions; and fundamentals work. The fundamentals effort involves development of advanced diagnostics for life assessments, quantification of erosion processes, and development of propellantless cathode technology.

The two focussed development activities conducted under the In Space program include: the next-generation ion propulsion system as follow-on to the Deep Space One system, utilizing a 10 kW ion engine; and development of 10-30 kW class high specific impulse (> 10,000 seconds) ion propulsion, applicable for interstellar precursor missions.

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High-Power Engine and Component Technologies
Develop/demonstrate 30 kW input power levels and above, at specific impulse levels to support human exploration of the solar system.

NSTAR-derivative Technologies
Develop component technologies for NSTAR-derivative high-throughput ion engines, and advanced power processing technology.

Sub-Kilowatt Ion Propulsion
Develop lightweight sub-kilowatt thruster and power processor technology.

Micro-Ion Propulsion
Evaluate feasibility of micro ion propulsion concepts.

Fundamentals
Enable high-quality lifetime assessments of high-thrust density ion propulsion via development of advanced diagnostics and understanding of erosion processes.

5/10-kW Next Generation Ion Propulsion
Develop the next-generation ion propulsion system as follow-on to Deep Space One system.

Interstellar Ion Propulsion
Develop high specific impulse (>10,000 seconds), 10-30 kW krypton ion engine to support interstellar space exploration.

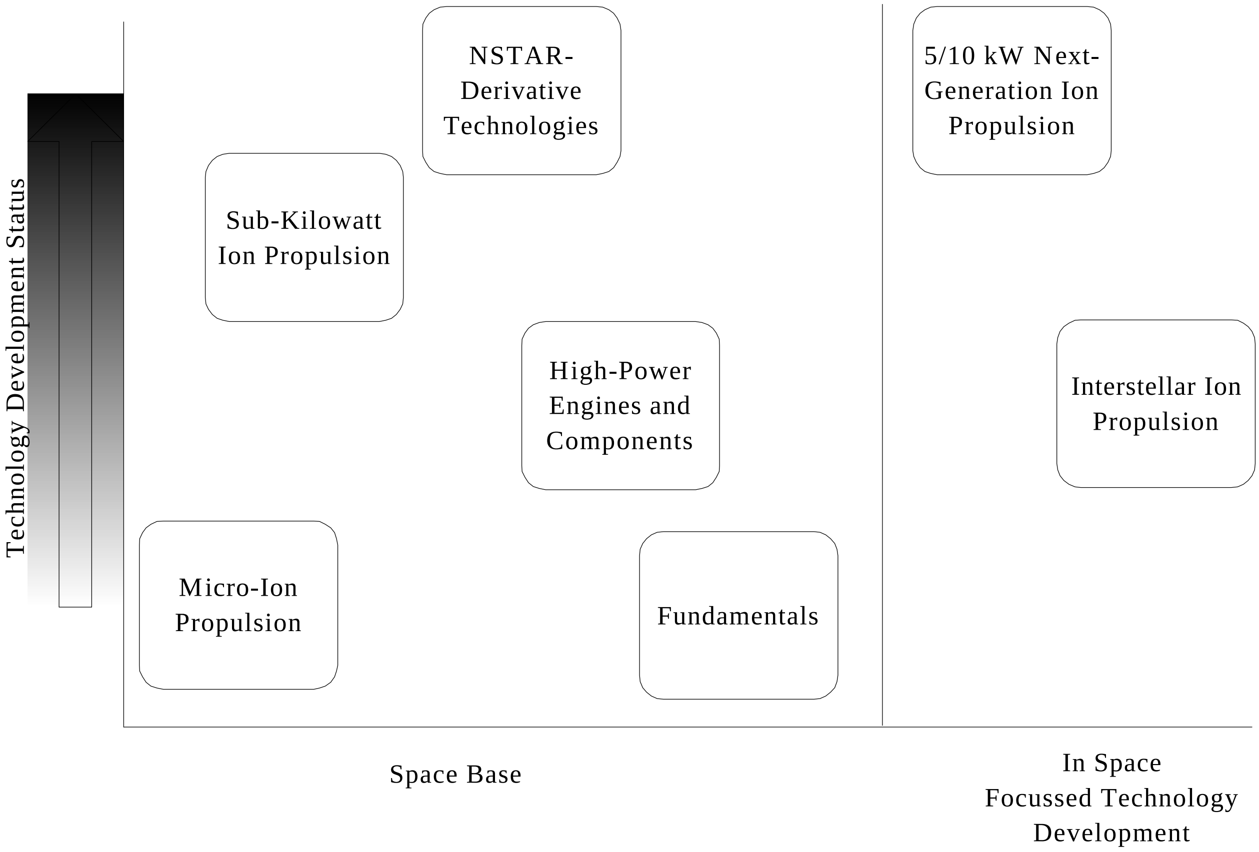

Figure 1 - Activities in the NASA ion propulsion program.

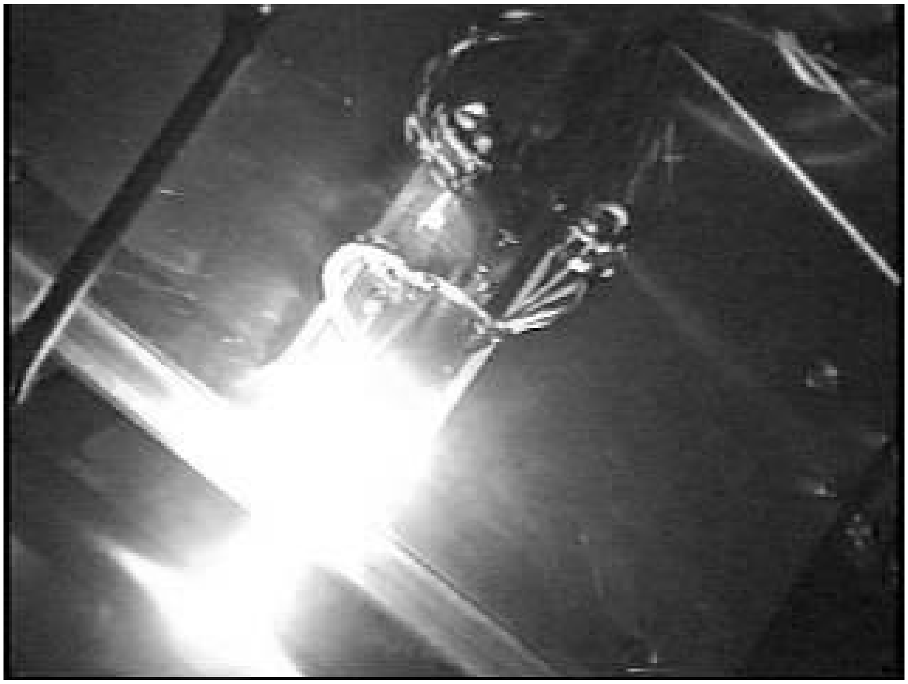

Figure 2 – Operation of a high-current hollow cathode.

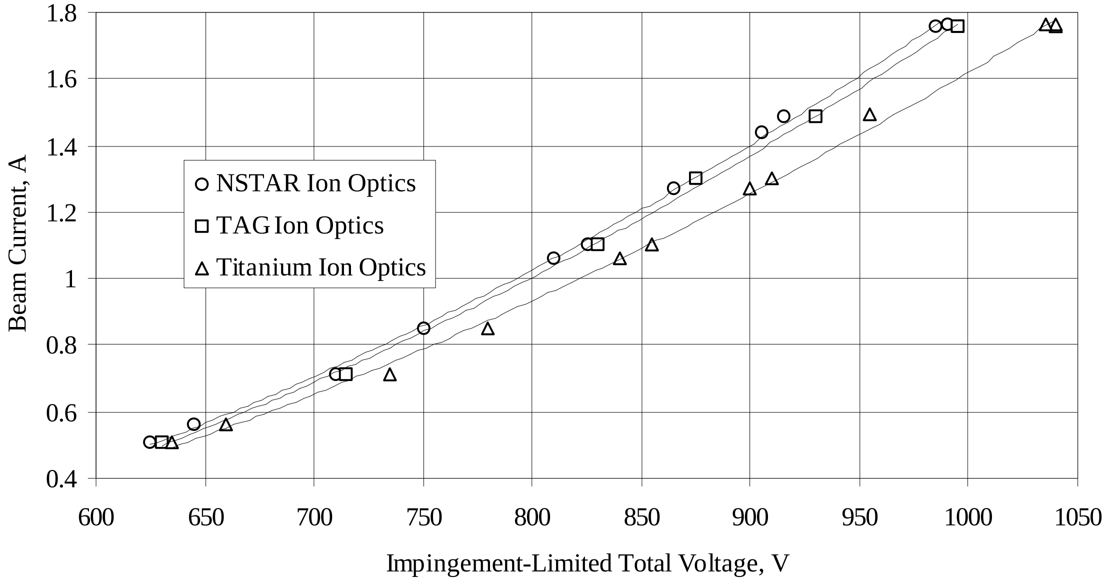

Figure 3 - Performance comparison of ion optics.

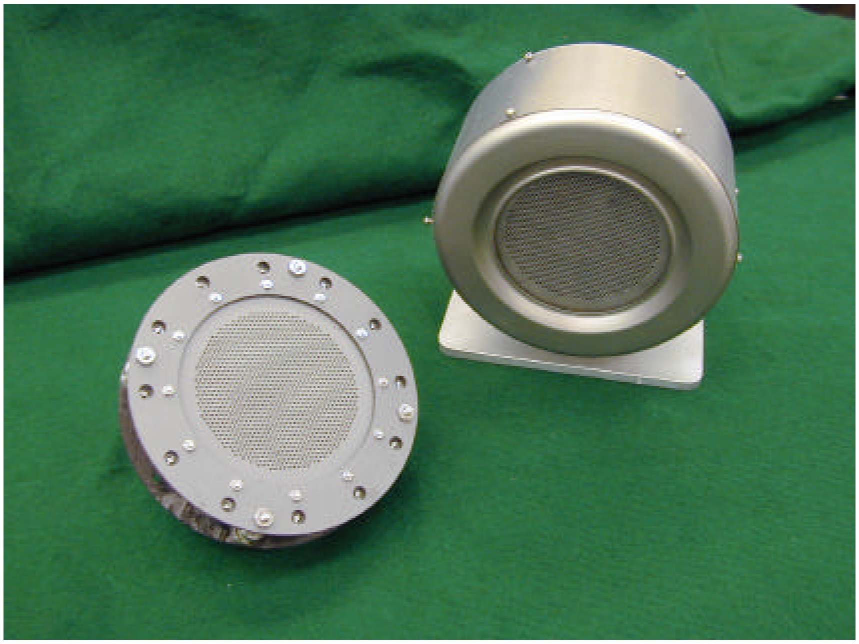

Figure 4 - 8 cm diameter pyrolytic graphite ion optics, shown with 8 cm engine.

Figure 5 – Second-generation sub-kilowatt breadboard power processor unit.

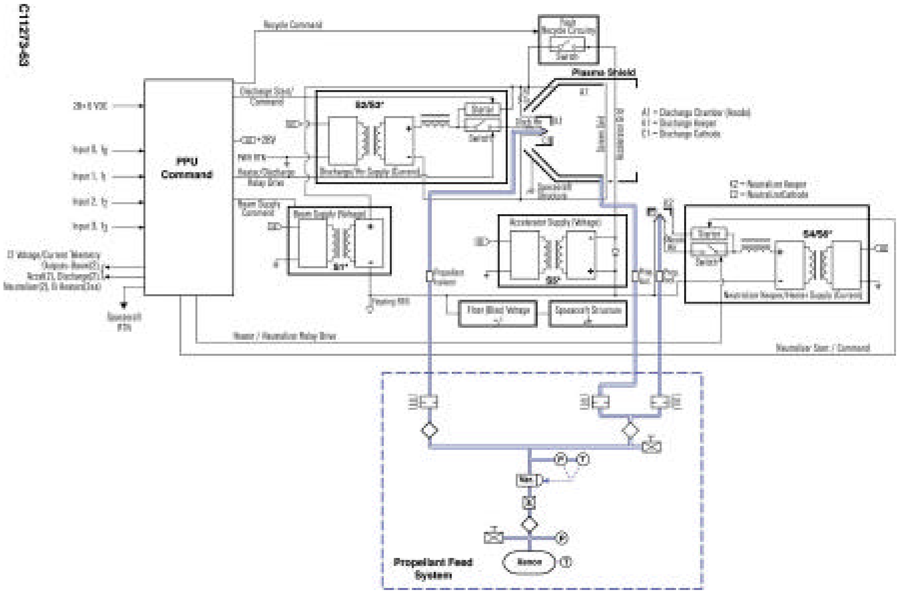

Figure 6 – Low power ion propulsion system diagram.

Figure 7 - HCMT operation with beam extraction.

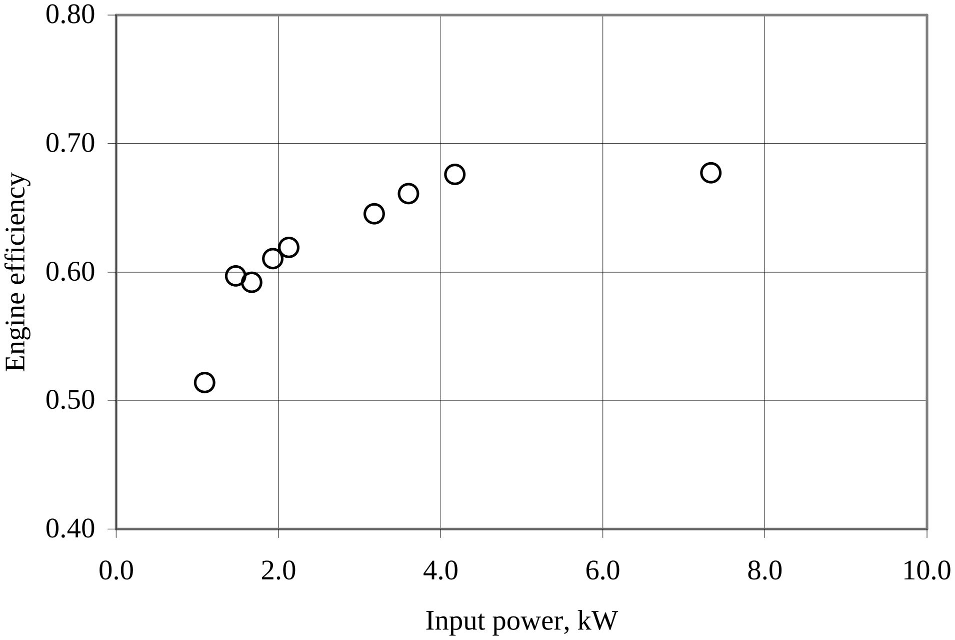

Figure 8 - 40 cm engine efficiency versus input power.

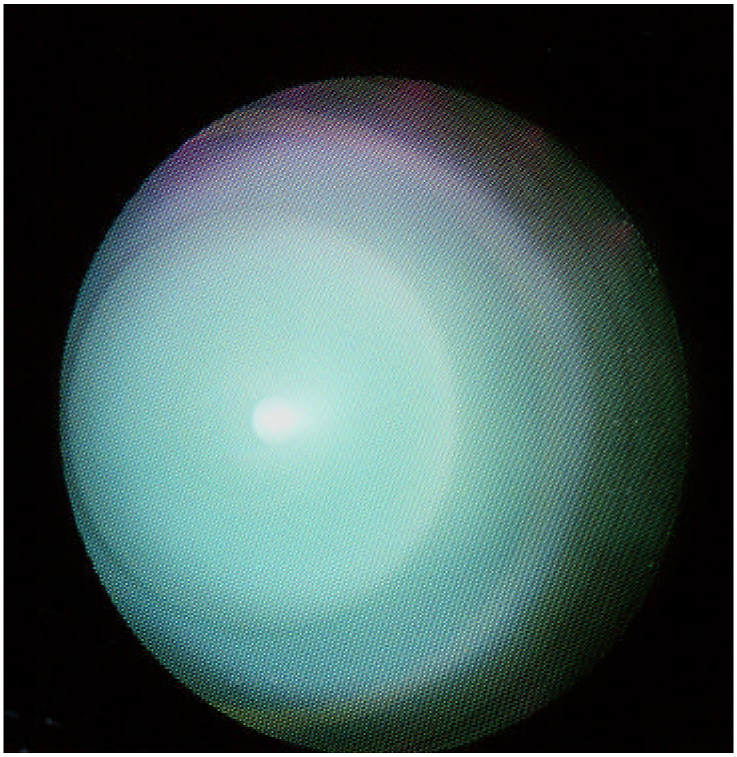

Figure 9 - 40 cm engine in operation.

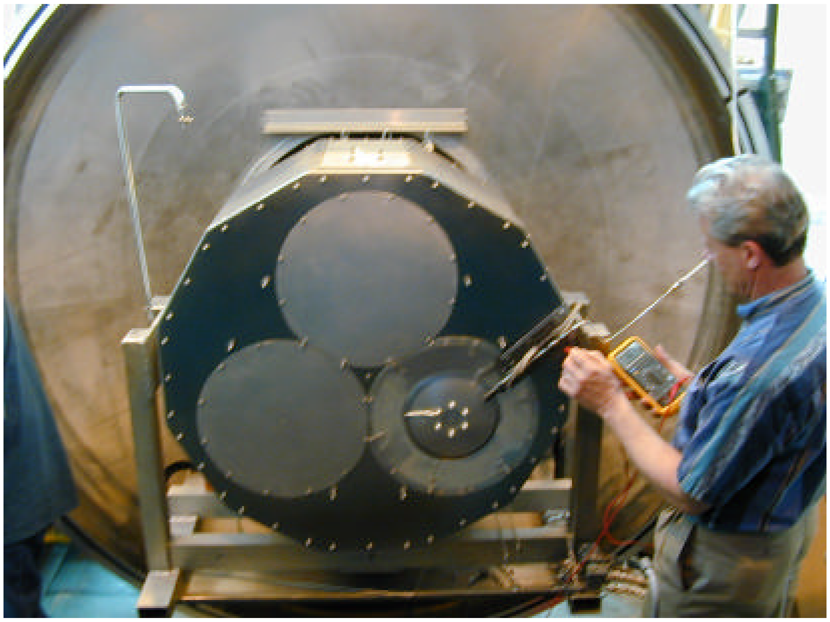

Figure 10 - Interstellar test-bed engine with sub-scale ion optics.

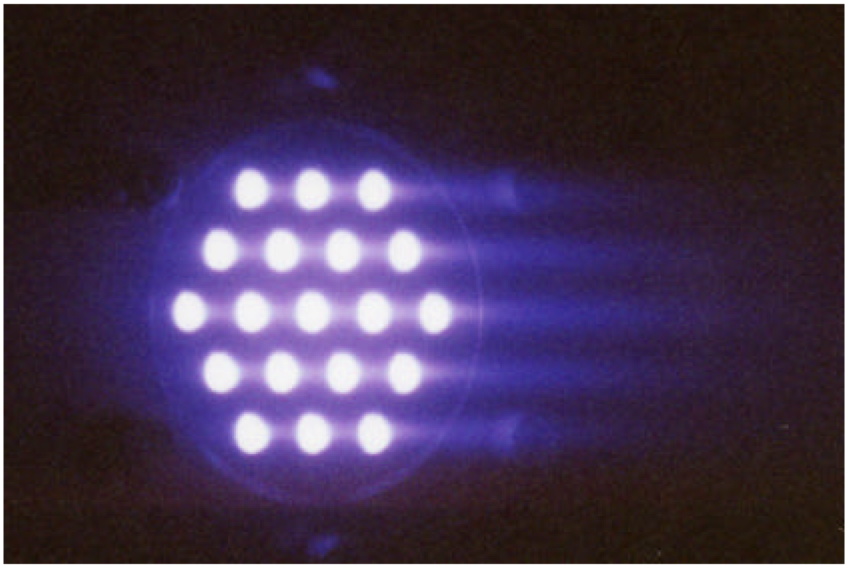

Figure 11 - Sub-scale ion optics test at >10,000 seconds specific impulse.