NASA/TM—2002-211877 AIAA–2002–3837

Microwave ECR Ion Thruster Development Activities at NASA Glenn Research Center

John E. Foster and Michael J. Patterson
Glenn Research Center, Cleveland, Ohio

October 2002

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2002-211877

AIAA–2002–3837

Microwave ECR Ion Thruster Development Activities at NASA Glenn Research Center

John E. Foster and Michael J. Patterson
Glenn Research Center, Cleveland, Ohio

Prepared for the
38th Joint Propulsion Conference and Exhibit
cosponsored by the AIAA, ASME, SAE, and ASEE
Indianapolis, Indiana, July 7–10, 2002

National Aeronautics and
Space Administration

Glenn Research Center

October 2002

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Microwave ECR Ion Thruster Development Activities at NASA Glenn Research Center

John E. Foster and Michael J. Patterson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Outer solar system missions will have propulsion system lifetime requirements well in excess of that which can be satisfied by ion thrusters utilizing conventional hollow cathode technology. To satisfy such mission requirements, other technologies must be investigated. One possible approach is to utilize electrodeless plasma production schemes. Such an approach has seen low power application <1 kW on earth-space spacecraft such as ARTEMIS which uses the rf thruster the RIT 10 and deep space missions such as MUSES-C which will use a microwave ion thruster. Microwave and rf thruster technologies are compared. A microwave-based ion thruster is investigated for potential high power ion thruster systems requiring very long lifetimes.

Nomenclature

$\vec{B}$	=	Magnetic Field
e	=	Elementary charge of an electron
$\vec{E}$	=	Electric Field
k	=	Boltzmann's constant
m_e	=	Electron mass
M_i	=	Ion mass
N	=	Cathode number
n	=	Plasma number density
q	=	Charge
T_e	=	Electron temperature
t	=	Time
ε_o	=	Permitivity of free space
Γ	=	Ion current density
w_μ	=	Microwave excitation frequency
w_{ce}	=	Electron cyclotron frequency

Introduction

Propulsion systems capable of providing a very high specific impulse (6000–9000 s) are desirable as primary propulsion options for far term missions to the outer planets and beyond. Gridded ion thruster systems are capable of satisfying such mission requirements. Ion thruster systems used for such an application will be required to operate continuously for perhaps as long as 4 to 10 years. Such continuous thrusting over long periods of time places stringent lifetime requirements on thruster components and subsystems. In general, thruster lifetime is limited by essentially 4 potential failure modes: 1.) discharge cathode failure, 2.) neutralizer failure, 3.) ion optics failure, and 4.) electron backstreaming. Failure modes 1 and 2 are related primarily to hollow cathode failure. Failure mode 3 is related to screen and accelerator grid degradation via erosion as well as grid to grid shorts arising from such erosion phenomena. Electron backstreaming becomes more and more of a problem as apertures widen due to grid erosion. High levels of backstreaming electrons can destroy the discharge cathode. One potential solution to this problem is the use of a magnetic grid.[1] Potential design solutions also exist for increasing the lifetime of the ion optics. These include the use of different electrode materials such as titanium[2] or carbon-based[3] or by simply increasing the electrode thickness[4]. Hollow cathode failure can occur after prolonged operation due to the depletion of barium in the insert brought on by simple barium diffusion and subsequent evaporation or the formation tungstates that tie up the barium. Because of such phenomena, ion thruster hollow cathodes may not be sufficient for those missions requiring a minimum of 4 years of continuous thruster operation.[5]

One possible solution is to utilize multiple cathodes. Ideally in this approach, the lifetime of the thruster would then be a factor of N times the average hollow cathode lifetime. Unfortunately, because these cathodes are also immersed in a plasma, they are also susceptible to erosion and possible insert contamination due to the deposition of backsputtered material. Additionally, discharge uniformity and stability can be expected to be very sensitive to a multiple cathode configuration. Another possible solution to the cathode lifetime issue is to simply replace it with another plasma production scheme that is less prone to failure over the course of long duration operation.

Electrodeless schemes such as inductive and microwave driven discharges are potential candidates. These schemes do not use cathodes and as a result, their lifetime is largely determined by the lifetime of the power supply or power tube.

In order to circumvent cathode lifetime issues particularly for high power thruster applications, a microwave thruster development program has been initiated at NASA Glenn Research Center. The purpose of this effort is to assess and develop this technology for high power applications.

State of the Art

The use of high frequency excitation to generate a discharge for ion thruster applications is not new. It was long recognized that this approach could circumvent problems associated with hollow cathodes such as lifetime and contamination. Of the many previously investigated electrodeless plasma production schemes, the inductive rf discharge and the microwave discharge approaches appear to be best suited for ion thruster applications. In the early 80s, TRW under contract with NASA Glenn Research Center developed two electrodeless concepts for ion thruster applications. They included an rf ion source and a microwave ion source.[6] The German space agency, DARA, has investigated rf driven inductive discharge concepts for ion thruster applications since 1960.[7] The basic thruster design consist of a ceramic or quartz discharge chamber around which an inductor coil is wrapped. The coil is excited at ~1 MHz. According to Faraday's law, this excitation induces electric fields into the discharge chamber that ultimately breakdown and sustain the discharge:

$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt} \qquad (1)$$

The time varying, induced electric field that imparts energy to the electrons is confined to within a skin depth of the discharge plasma. These processes are illustrated in Figure 1. Conventional ion optics and a hollow cathode neutralizer are used to extract and neutralize the ion beam respectively. In this respect, though the discharge cathode lifetime issues can be mitigated, the neutralizer lifetime is presently limited to the state of the art (~28,000 hours). One example of this technology has been applied for orbit raising/station-keeping applications on-board the ARTEMIS spacecraft. The ARTEMIS rf ion thruster is a 10 cm device delivering 20 mN of thruster at 600 W input power.[8]

The Japanese Space Agency, ISAS, has developed to flight level readiness a 10 cm (300W) microwave excited ion thruster for an asteroid sample return mission.[9] Also ongoing within ISAS are development activities aimed at scaling up size and power of the microwave thrusters.[10] In these engines, the discharge plasma is produced via electron cyclotron resonance (ECR). This process is based on electron resonant absorption of electromagnetic radiation at the cyclotron frequency. At resonance, the electrons can gain energy continuously:

$$w_{\mu} = w_{ce} \qquad (2)$$

Ionization and subsequent plasma production occurs when these energetic electrons collide with neutrals. The basic ECR process is illustrated in Figure 1. The ISAS thrusters utilize permanent magnets to establish ECR zones. The ISAS microwave thruster also features a microwave driven neutralizer. An antenna located in the vicinity of an ECR zone sustains the neutralizer plasma. Electrons from the resulting plasma are extracted via a keeper-like electrode. Because this approach replaces both the discharge and the neutralizer hollow cathode, cathode contamination issues and (to a limited extent) thruster lifetime issues are minimized.

Comparison between rf and microwave schemes

Both the rf and the microwave ion thruster approaches offer potential design solutions for achieving a long life discharge chamber. However, the microwave ECR discharge approach has several distinct features that make it desirable particularly for missions requiring high power thruster operation and very long thrusting times. In general, inductive rf sources require a higher neutral discharge chamber pressure (0.1–1 mTorr) than ECR sources (0.01–1 mTorr).[11] ECR sources are capable of operating at discharge chamber pressures potentially less than conventional DC ion thrusters. Operating at a reduced discharge chamber neutral background pressure reduces charge exchange erosion of the ion optics and thus increases thruster lifetime. The operating discharge neutral pressure of an rf ion source is related to mechanism by which rf energy is coupled to the electrons. The excitation frequency for rf sources must closely match the electron-neutral collision frequency. This assures that the electron gains maximum energy between collisions. Arbitrarily increasing the frequency necessarily increases the background pressure requirement. At frequencies and pressures below optimum, ionization efficiencies decrease due to a reduced electron-neutral collision frequency.

ECR discharges for a given input power and pressure are capable of generating higher plasma densities than a conventional rf inductive source.[12] In this respect, for similar applications, the ECR ion source can be expected to be more compact and have a higher propellant efficiency. This difference is related to the way in which power is transferred to the electrons. In an ECR source, electrons continuously gain energy in a reduced neutral background. Generally speaking, electrons in the rf source can only gain energy during a half cycle, between collisions. In this respect, the maximum energy gain over a cycle per electron is greater in the ECR source. The maximum plasma density that can be obtained in a conventional ECR sources is related to the plasma frequency. For absorption to occur, the microwave frequency must be greater than the plasma frequency. There are, however some exceptions to this case. If the microwaves are launched from a high field to a low field region, then it is still possible for the microwaves to be absorbed and thereby achieve higher plasma densities than the limit set by the plasma frequency.

Rf discharges feature either an external or internal antenna. In the case of an external antenna, the discharge chamber is typically quartz or ceramic. Under conditions of long duration operation, backsputtered material from the optics can coat the discharge chamber thereby affecting the coupling of the rf into the gas.[13] For rf sources featuring internal antenna, the requirement that the discharge chamber be made of an insulator can be relaxed. However, because the antenna is immersed into the discharge, it will be subject to sputtering which could limit the service life of the antenna or contribute to the formation of flakes between the ion optics. Microwave sources do not require antennas. Instead, the microwave energy can be channeled to the discharge chamber via waveguide. As long as the waveguide is not immersed in a magnetic field of strength sufficient for ECR, no plasma will form there and thus the microwaves can be cleanly transported into the discharge chamber.

Microwave ion sources are well adapted for clustering. An array of engines including the neutralizers could be operated via a remote microwave power tube and a power divider. Reflected power could be directed to dummy load/radiator. Engineering an rf thruster cluster is not as straightforward since each thruster antenna coil would likely be required to have its own matching network.

Finally, because rf sources operate at lower frequencies, the antenna can induce eddy currents into surrounding structures. These currents are resistive in the conductive materials and therefore represent a power loss mechanism. One possible method of mitigating this problem is to use a magnetic shielding material with a high frequency response. Researchers at Giessen University has investigated the use of ferrites to shield the time varying magnetic field so that eddy current formation in surrounding materials is minimized.[14] In this approach, a ferrite pot slips over the discharge chamber. One concern regarding this approach is associated with antenna temperature. At high power operation, the heat load from antenna can drive the ferrite above its Curie temperature thereby destroying its shielding properties. Additionally, ferrites are very brittle and therefore very sensitive to strain and mechanical shock. Large ferrite pots may be susceptible to damage when exposed to significant vibrations.

While rf ion sources hold great potential, particularly for low-to-medium power applications, the advantages associated with the microwave driven discharge particularly at higher powers motivated the decision to investigate the microwave ECR source as a potential design solution for a long life, high power ion thruster discharge plasma source.

Design considerations and Experimental Hardware

The approach taken to the development of a high power, microwave-driven ion thruster was to essentially use existing high power ion thruster heritage such as NSTAR and the 10 kW 40-cm thruster[15] and essentially replace the cathode assembly with a microwave applicator. With the exception of the discharge and neutralizer cathodes, all other thruster components would remain unchanged. This approach is similar to that implemented by Divergilio et al.[6] The integration of the microwave approach would then be to extend the discharge and neutralizer cathodes' lifetime while at the same time utilize existing grid and magnetic circuit technologies. This low risk approach has the potential to greatly reduce overall development time.

Design considerations

The goal of microwave thruster development activity is to design and build an ECR ion thruster capable of delivering a 5 A ion beam at a microwave input power of 1 kW or less. As a starting point, a 40-cm ion thruster (10 kW class) discharge chamber was modified and retro-fitted with a cylindrical waveguide port at the discharge chamber backplate. The discharge chamber utilizes five permanent magnet rings configured in a ring cusp geometry. Microwave power is to be injected on centerline as illustrated in Figure 2. The maximum extractable ion current depends primarily upon the plasma density and the electron temperature:

$$\Gamma = 0.61 \cdot n \cdot \sqrt{\frac{k \cdot T_e}{M_i}} \qquad (3)$$

Thermal, background electron temperatures are expected to range between 2 and 5 eV. The maximum plasma density obtainable for the discharge chamber of this configuration depends primarily on the excitation frequency. The microwaves injected into the discharge chamber from the discharge chamber backplate enter regions of electron resonance from the low field side of the magnetic cusps. Electron cyclotron resonance takes place at the loci of points near magnetic cusps. Here electrons are heated to ionization energies and plasma is produced. This plasma in the ECR zones can reach a maximum density determined by the condition where the plasma frequency equals the local plasma frequency. Where

$$\omega_p = \sqrt{\frac{n \cdot e^2}{m_e \cdot \varepsilon_o}} \tag{4}$$

and

$$\omega_{ce} = \frac{B \cdot q}{m_e} \tag{5}$$

At plasma densities higher than the criterion established by the condition $\omega_c = \omega_p$, the microwaves are no longer absorbed, but reflected to regions of lower field strength.

In order to satisfy the requirement of a 5 A ion beam extracted from a 40-cm diameter ion extraction surface, an operating frequency of 5 GHz was chosen. At 5 GHz, the maximum plasma density obtainable within the discharge chamber is $3.08 \cdot 10^{11}$ #/cm^3. Assuming a conservative estimate of 4 eV for the electron temperature, the maximum ion current density at the plane of the ion extraction optics would be 50A/m^2. For 40-cm diameter ion optics, the maximum extracted beam would be of order 6.3 A.

With the selection of the operating frequency set, the next step is then to select a microwave power source. Solid state microwave power modules similar to those used in the MUSE-C program are limited to ~100 W and are therefore not applicable for high power thruster applications (~1 kW).[9] In this case, a conventional microwave power tube must be used. Primary considerations for the microwave power tube include lifetime, output power, efficiency, complexity, and robustness. Of the microwave power tubes available today, the magnetron oscillator is by far the most efficient, with electrical power conversion efficiencies as high as 80%.[16] Additionally, the physical construction of the magnetron is simple and robust. Figure 3 depicts the general layout and operation of a magnetron. The magnetron is a cross-field device in which a radial electric field is established between the anode and coaxial cathode. The trajectories of electrons emitted from the cathode are determined by the combination of the radial electric field force and the magnetic force generated by an imposed axial magnetic field. Electrons interact with microwave oscillations near resonant cavities at the anode. As electrons orbit the cathode in the space between the two electrodes, they give up energy to the microwave field. This energy is extracted via an antenna located in one of the resonant cavities. Magnetrons are capable of supplying high average power (~100 W to 5 MW).[16] Presently, the drawback of the magnetron is lifetime. The lifetime of the tube is determined largely by the life of the cathode which is presently of order 20,000 hrs.[17] The extension of magnetron lifetime is an active area of research. With improved designs, the lifetime of these devices should increase significantly.

Another high power tube that could potentially be applicable for ion thruster plasma generation is the klystron. Unlike the magnetron, the klystron is an amplifier tube. Microwave power is generated by the interaction between an electron beam and discrete coupling cavities as illustrated in Figure 3. A low power microwave signal from an oscillator is injected into the tube. The electron beam interacts with these oscillations. As the electrons pass by each cavity, interactions with the rf gives rise to the formation of electron bunches.[18] The electron bunches grow as they pass through each cavity, amplifying the RF along the way. Amplification occurs discretely at each cavity. Ultimately the electron beam is terminated at a collector electrode. These tubes are capable of supplying average power over a wide range (1 kW–100 MW). The electrical efficiency of this device ranges between 30% and 70%.[16] Estimated lifetimes of klystrons are of order 50,000 hrs.[19]

The traveling wave tube (TWT) is another microwave source that is potentially capable of satisfying mission requirements. The TWT is also depicted in Figure 3. This device utilizes a continuous slow wave structure for microwave amplification. An oscillator signal excites the slow wave structure. The electron beam continuously interacts with the RF field along this structure, amplifying it as it progresses down the axis. The interaction between the electron beam and the rf in a helical TWT can take place because the effective rf axial velocity is reduced due to the pitch of the helix (its effective axial pathlength is longer along the helix). Traveling wave tubes have are capable of generating average powers from 10 W up to 50 kW at electrical efficiencies ranging between 30% and 40 %.[16] These tubes however have demonstrated life in excess of 100,000 hrs. Additionally, such long lifetimes have been demonstrated during on-orbit operation (communication satellites).[20] In this regard, there is a rich space heritage. Recent studies indicate TWT cathode lifetimes of order 200,000 hrs.[21] Even though the efficiency of the TWT is lower than that of the klystron and the magnetron, for very high specific impulse applications, the discharge power is only a small fraction of the total input power. In this regard, the reduced efficiency of the TWT may not be an issue. Based on this brief overview of tube characteristics, it would appear that the TWT possesses the best combination of lifetime, efficiency, and power for high power, long duration missions.

Experimental Hardware Approach

As mentioned earlier, the microwave ion thruster discharge chamber to be used in this study is a 40-cm partial conic discharge chamber fabricated from mild steel. The magnet rings are made up of samarium cobalt magnets. At an operating frequency of 5 GHz, the electron cyclotron resonance condition occurs near the magnet ring surface along the 1790 G contour.

Traditionally, the microwave power is input into vacuum vessel via a dielectric window that separates the vacuum from the ambient. Prolonged absorption of high power microwaves can reduce the useful life of the window. One appeal of the vacuum window set-up however, is that it is a physical barrier separating the plasma from the microwave waveguide. In this study, the microwave power will be fed into the discharge chamber using a novel approach. Microwave power from the power tube will be fed into a waveguide to coax power divider. The divider divides the input power 4 ways so that no coax line carries over 250 W of microwave power for input powers up to 1 kW. In the configuration proposed here, plasma formation inside the cylindrical waveguide is not likely for at least two reasons: 1) The magnetic field at all points inside the waveguide is non-resonant with the microwave frequency 2) The magnetic field at the exit plane of the waveguide is cusp-like. The dB/dz mirror force associated with this magnetic field geometry tends prevent the backflow of plasma into the waveguide.

The complete microwave power train set up is illustrated in Figure 4. As illustrated in the figure, the microwave power from the tube passes through a circulator, directional coupler, and three stub tuner on the way to the power divider. The purpose of the circulator, a non-reciprocal device, is to prevent microwave power reflected at various boundaries from returning to the power tube, possibly damaging it. The atmosphere side of the power train consists almost exclusively of rectangular waveguide. In the rectangular waveguide, the dominant mode TE_{01} excitation mode is set up. This mode is illustrated in the Figure 5. The coaxial cable carry the microwave power into the vacuum tank. On the vacuum side, the coaxial cable feeds into high voltage DC blocks which are used to isolate the thruster from tank ground. The DC blocks pass rf but appear as an open circuit element to DC. From the DC blocks, the coaxial cable will then feed into a power combiner that combines the power of the 4 lines into a waveguide, single port output. This output mates to a directional coupler which itself is connected directly to a cylindrical waveguide coaxially mounted to the thruster. The directional coupler at this location should give an accurate measurement of forward and reflected power at the engine. The cylindrical waveguide contains a sliding short plunger whose position can be varied via a stepper motor. The transition between the rectangular waveguide at the directional coupler and the cylindrical waveguide gives rise to a mode conversion from TE_{01} (the dominant rectangular mode) to a cylindrical TE_{11} (the dominant cylindrical mode), both of which are illustrated in Figure 5.

A cylindrical waveguide for injection was chosen primarily because of symmetry (the thruster is cylindrically symmetric). The combination of the tuning plunger in the cylindrical waveguide and the discharge chamber can act as a tunable resonant cavity. Varying the quality factor of the tuning cavity can aid in the initiation of the discharge. (The quality factor of a resonant circuit is defined as the ratio of the resonance frequency to the difference between the two frequencies at which only half the power at resonance is dissipated.)

Preliminary test configuration

In order to expedite a preliminary test of the discharge performance and of the power delivery system in a cost effective manner, a 2.45 GHz magnetron power tube will be utilized. The power train set-up is similar to that illustrated in Figure 4. A photograph of the thruster is shown in Figure 6. The thruster features a copper cylindrical waveguide microwave applicator fitted with a stepper motor driven sliding short. At 2.45 GHz, the maximum extractable beam is estimated to be of order 2 A.

In addition to the thruster development, a microwave driven neutralizer is also being investigated. A photograph of the actual hardware is shown in Figure 7. The device is of similar design described in reference 22. The primary differences include antenna type and magnetic circuit. The helical antenna was selected primarily because it has the capacity to generate an axially directed, circularly polarized microwave beam.[23] In this respect, the microwaves can be used to inject the microwaves directly into the ECR zone from the high field side. This approach maximizes the plasma density generated in the device.[11] The neutralizer operates at 6 GHz generated by 0-100 W, TWT-based microwave power module. The higher operation frequency increases the plasma density and thus increases the extractable electron current. Perhaps the biggest challenge in regards to the microwave neutralizer is increasing the output current. Unlike a hollow cathode discharge where copious amounts of electrons are emitted thermionically, in a microwave cathode, there is typically no other electron production mechanism besides direct impact ionization. In this regard, the maximum extractable current is a function of plasma density and electron temperature only. An additional concern is related to antenna erosion inside the neutralizer. Because the antenna is immersed in a plasma, it will be subject to ion bombardment. An investigation into mitigating this problem by either considering alternative methods of introducing the microwaves into the device or by determining a means to reduce plasma potentials near the antenna is being actively pursued.

Conclusion

In order meet ion thruster lifetime requirements for those missions requiring thrusting times of order four to 10 years, an alternative plasma production scheme is being investigated. A microwave driven ECR source could potentially satisfy mission requirements for those missions requiring long thrusting times. As compared to inductive rf sources, ECR sources possess potential advantages such as reduced charge exchange erosion rates and ease of clustering.

References

[1] Foster, J.E., Roman, R., Soulas, G.S., and Patterson, M.J., "Magnetic Grid for Electron Backstreaming Mitigation," IEPC Paper 01–221, 2001.

[2] Soulas, G.C., Foster, J.E., and Patterson, M.J., "Performance of Titanium Optics on a NASA 30 cm Ion Thruster," AIAA Paper 2000–3814, July 2000.

[3] Haag, T, Patterson, M.J., and Soulas, G.C., Carbon-Based Ion Optics Development at NASA GRC, IEPC Paper 01–094, 27th IEPC, Oct. 2001.

[4] Soulas, G.C., "Improving total impulse capability of the NSTAR Ion Thruster with Thick-Accelerator –Grid Ion Optics," IEPC Paper 01–081, 27th IEPC, Oct. 2001.

[5] Kovaleski, S.D., Patterson, M.J., Soulas, G.C., and Verhey, T.R., "A Review of Hollow Cathode Testing for the International Space Station Plasma Contactor," IEPC Paper 01–271, 27th IEPC, Oct. 2001.

[6] Divergilio, W.F., Goede, H., and Fosnight, V., "High Frequency Plasma Generators for Ion Thrusters," NASA Contract Report: NASA CR–167957, November, 1981.

[7] Groh, K.H. and Loeb, H.W., "State of the Art of Radio Frequency Ion Thruster,", *Journal of Propulsion and Power*, Vol. 7, No. 4, July-August 1991, pp. 573–579.

[8] Killinger, R., Bassner, H., Kukies, R., and Leiter, H., "Results of the 15000 Hr. Lifetest of the RIT 10 Ion Propulsion of ESA's ARTEMIS Satellite," IEPC Paper 01–82, 27th IEPC, Oct. 2001.

[9] Kuninaka, H., Satori, S., Funaki, I., Shimizu, Y., and Toki, K., "Endurance Test of Microwave Discharge Ion Thruster System for Asteroid Sample Return Mission MUSES-C," IEPC Paper 92–137, 26th IEPC, Cleveland, 1997.

[10] Toki, et al., "Performance Tests of Various Discharge Configurations for ECR Ion Thruster," IEPC Paper 01–91, 27th IEPC, Pasadena, 2001.

[11] Conrads, H. and Schmidt, M., "Plasma Generation and Plasma Sources," *Plasma Sources Sci. Technol.*, Vol. 9, 2000, pp. 441–454.

[12] Lieberman, M.A and Lichtenberg, A.J., Principles of Plasma Discharges and Materials Processing, John Wiley and Sons, NY, 1994, pp. 412–433.

[13] Sovey, J.S., Dever, J.A., and Power, J.L., "Retention of Sputtered Molybdenum on Ion Engine Discharge Chamber Surface," IEPC Paper 01–86, 27th International Electric Propulsion Conference, Pasadena, CA, October 2001.

[14] Lenz, B., Schweitzer, M., and Loeb, H.W., "Improved RF-Coupling Methods for RIT-Engines, AIAA Paper, 1979.

[15] Patterson, M.J, et al., "Next Generation 5/10 kW Ion Propulsion Development Status," IEPC 01–89, 2001.

[16] Scott, A.W., Understanding Microwaves, John Wiley and Sons, Inc., NY, 1993, pp. 283–317.

[17] http://www.eren.doe.gov/power/tech_access/docs/r_99_503.cfm#tech (accessed June 28, 2002)

[18] Gilmour, A.S., Microwave Tubes, Artech House, Norwood, MA, 1986, pp. 201–238.

[19] Park, S.S. et al., "Reliability Analysis of Klystron-Modulator System," *Proceedings of the Second Asian Particle Accelerator Conference*, Beijing, China, 2001.

[20] Hansen, J.W., "US TWTs from 1 to 100 GHz," *Microwave Journal*, 1989, Vol. 32, pp. 179–183.

[21] Dieumegard, D. et al., "Life test performance of thermionic cathodes," *Applied Surface Science*, Vol. 111, Feb. 1997, pp. 84–89.

[22] Satori, S., Funaki, I., and Kuninaka, H., "Plasma Coupling of Microwave Neutralizer," AIAA Paper 98–3478, 34th AIAA Joint Propulsion Conference, Cleveland, 1998.

[23] Chang, K. editor, Handbook of Microwave and Optical Components, Vol. 1 (Microwave Passive and Antenna Components), "Helical Antennas," by Schwering, F.K., and Mink, J.W., John Wiley and Sons, New York, 1989, pp. 647–653.

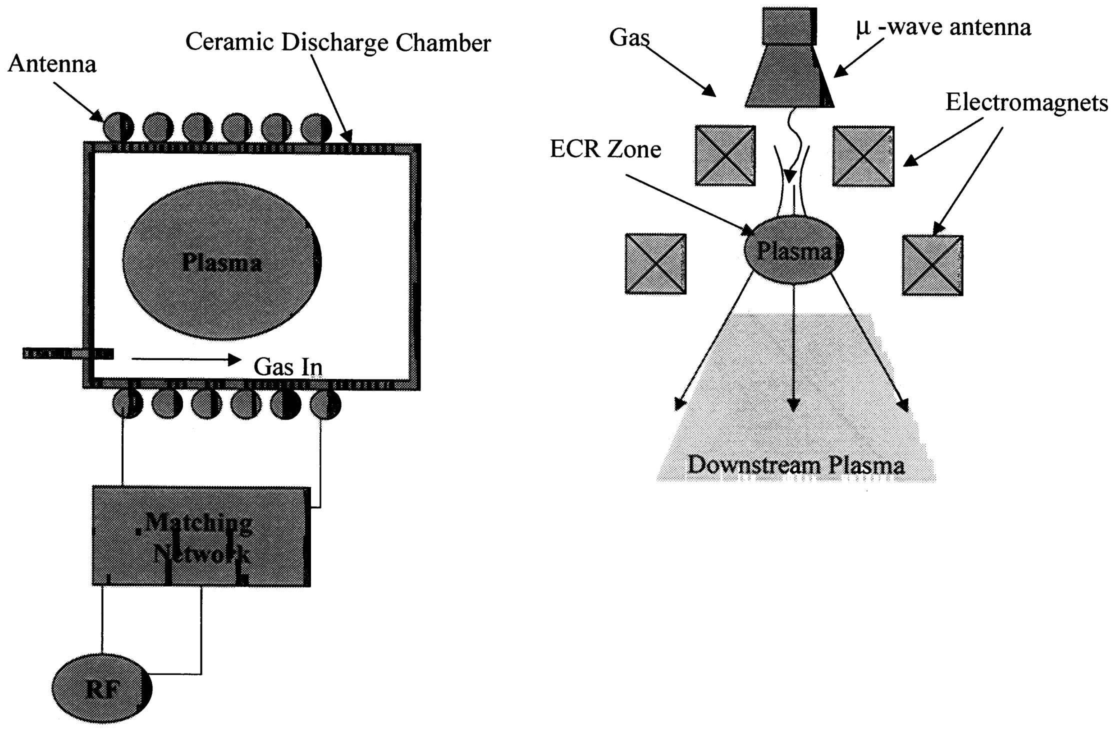


Figure 1. Simplified depiction of an inductive rf discharge and a microwave ECR discharge. These electrodeless plasma production schemes are readily adaptable for ion thruster applications.

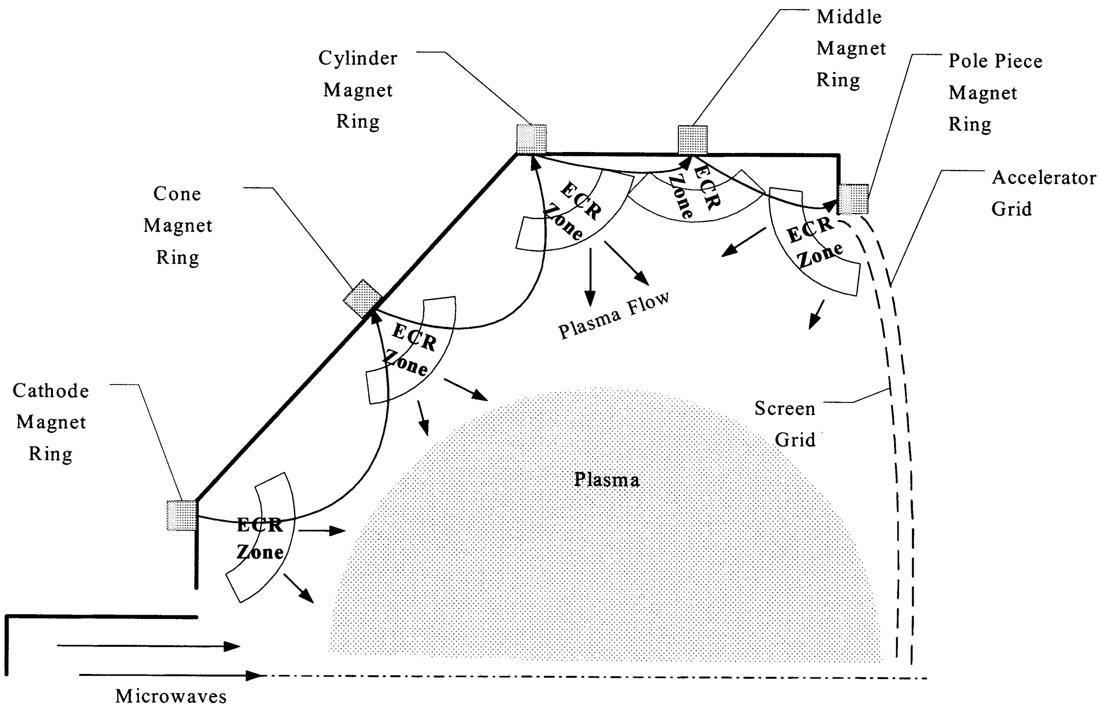


Figure 2. Electron cyclotron resonance ion thruster. Notice ECR zones above each magnet ring.

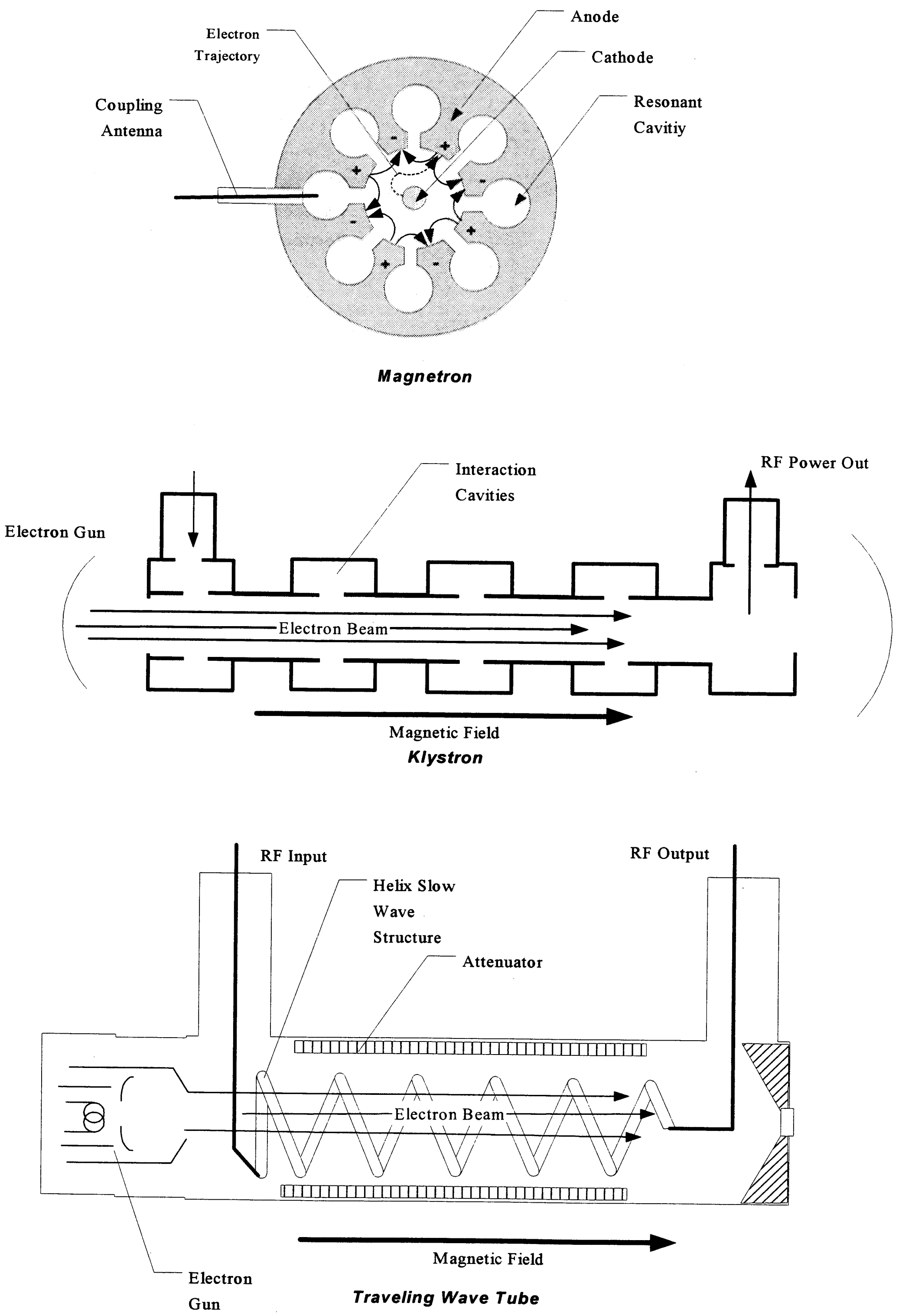


Figure 3. Operating principles of three candidate microwave power tubes.

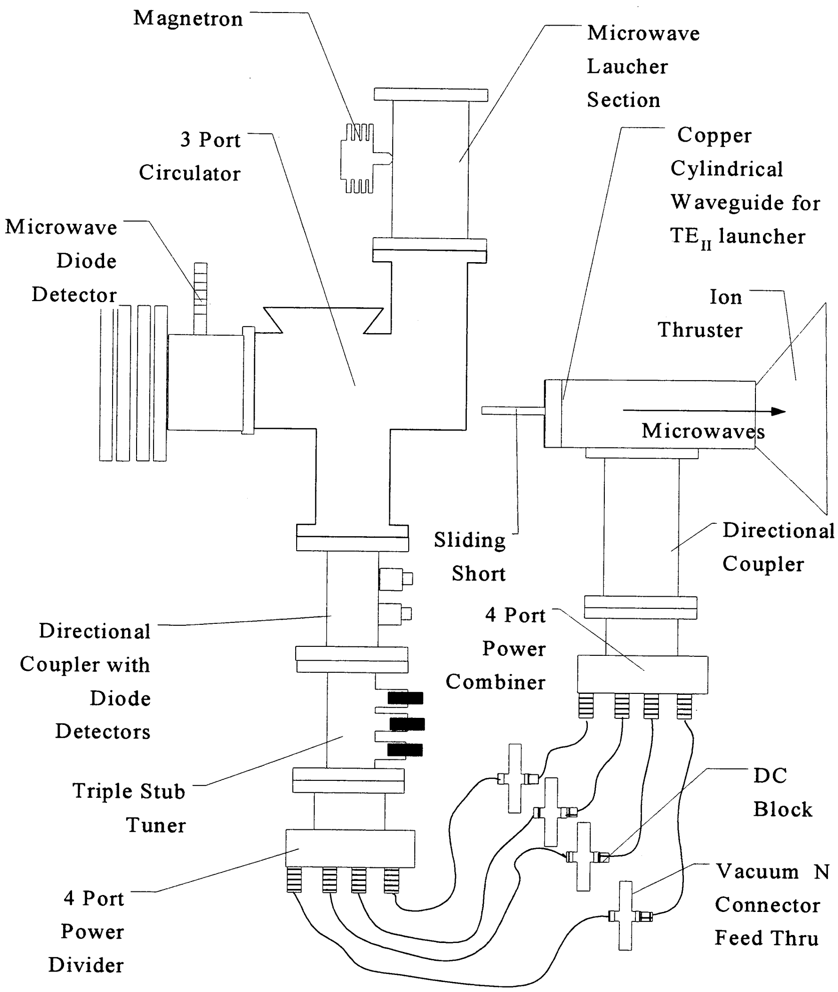
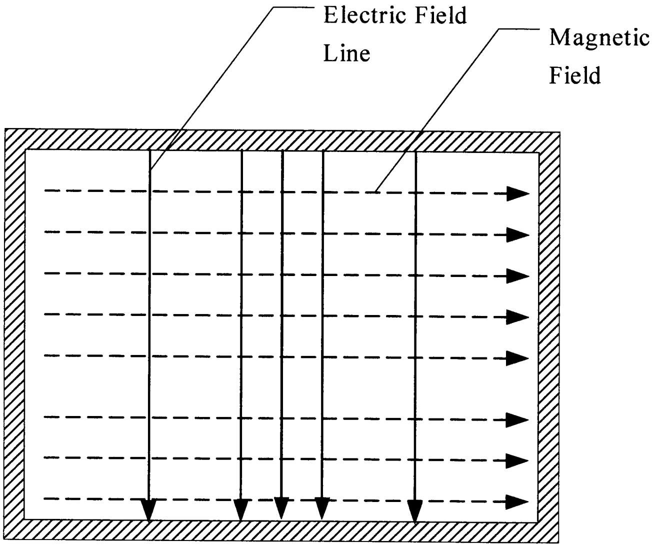
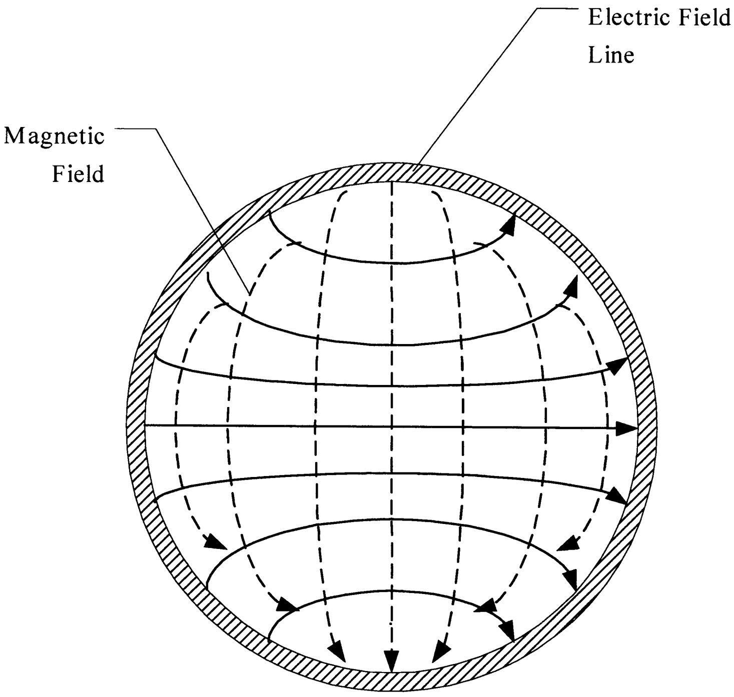


Figure 4. Depiction of the microwave power train extending from the power tube to the ion source. Power dividers eliminate the need for a microwave vacuum window.



Rectangular TE $_{01}$ Mode



Cylindrical TE $_{11}$ Mode

Figure 5. Cross sectional view of electromagnetic field patterns inside waveguide for the dominant mode Te_{01} (rectangular) and the dominant mode TE_{11} (cylindrical).

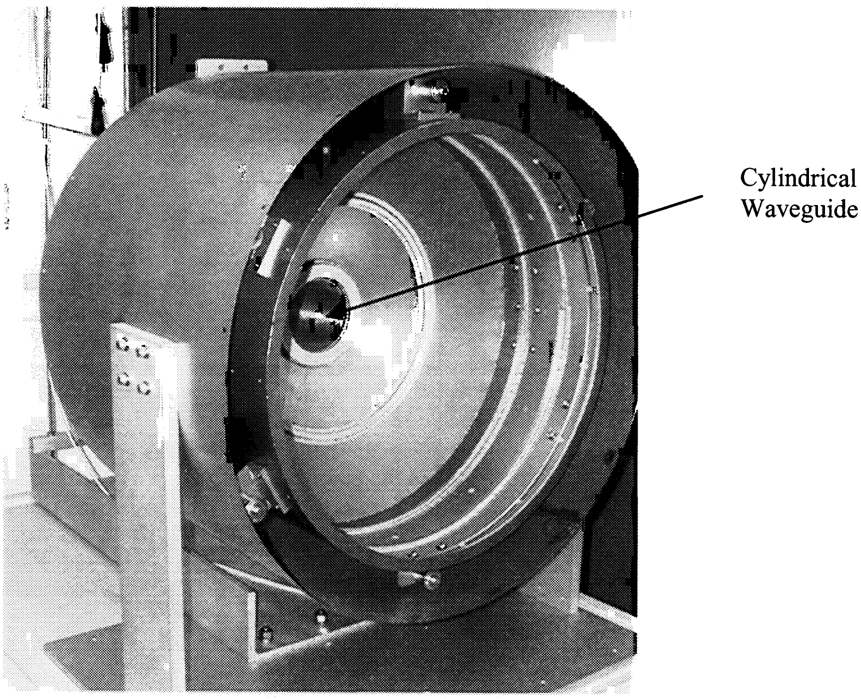


Figure 6a. Photograph of the microwave thruster with ion optics removed. Ion optics diameter = 40 cm.

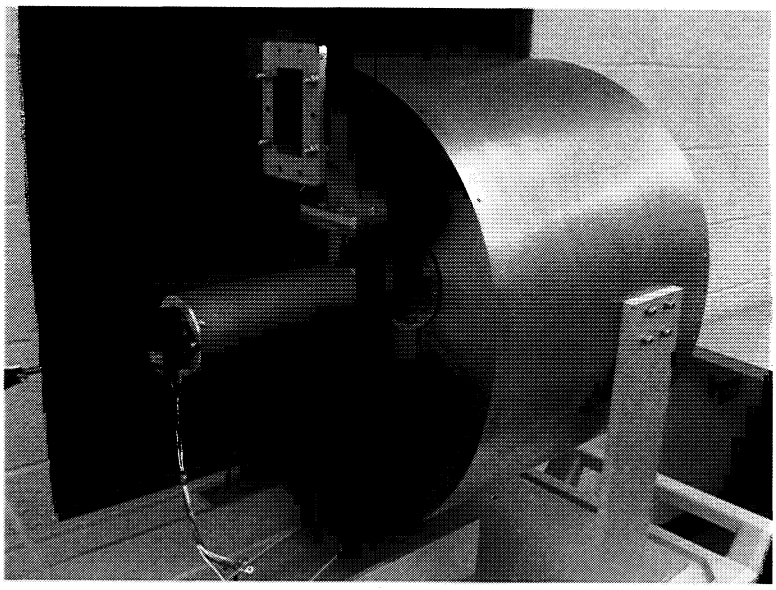


Figure 6b. Rear view of microwave ion thruster. Cylindrical waveguide shown with E-plane bend waveguide.

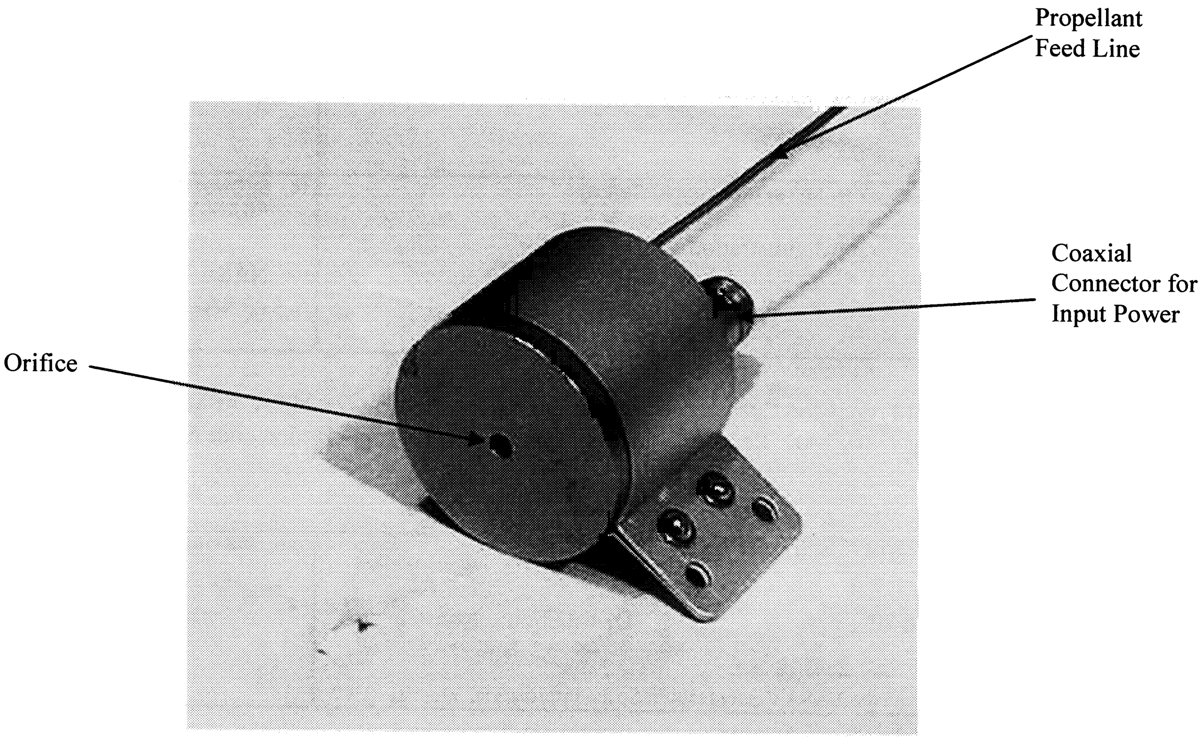


Figure 7. Microwave-driven neutralizer. This design features a helical antenna.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 2002

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Microwave ECR Ion Thruster Development Activities
at NASA Glenn Research Center

5. FUNDING NUMBERS
WU–755–B4–04–00

6. AUTHOR(S)
John E. Foster and Michael J. Patterson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–13559

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2002-211877
AIAA–2002–3837

11. SUPPLEMENTARY NOTES
Prepared for the 38th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Indianapolis, Indiana, July 7–10, 2002. Responsible person, John E. Foster, organization code 5430, 216–433–6131.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 20 and 70 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
Outer solar system missions will have propulsion system lifetime requirements well in excess of that which can be satisfied by ion thrusters utilizing conventional hollow cathode technology. To satisfy such mission requirements, other technologies must be investigated. One possible approach is to utilize electrodeless plasma production schemes. Such an approach has seen low power application <1 kW on earth-space spacecraft such as ARTEMIS which uses the rf thruster RIT 10 and deep space missions such as MUSES-C which will use a microwave ion thruster. Microwave and rf thruster technologies are compared. A microwave-based ion thruster is investigated for potential high power ion thruster systems requiring very long lifetimes.

14. SUBJECT TERMS
Hollow cathode; Microwave; Electrodeless; Plasma; Ion thruster

15. NUMBER OF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102