Fundamentals of Electric Propulsion

Ion and Hall Thrusters

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Note from the Series Editor

The Jet Propulsion Laboratory (JPL) Space Science and Technology Series broadens the range of the ongoing JPL Deep Space Communications and Navigation Series to include disciplines other than communications and navigation in which JPL has made important contributions. The books are authored by scientists and engineers with many years of experience in their respective fields, and lay a foundation for innovation by communicating state-of-the-art knowledge in key technologies. The series also captures fundamental principles and practices developed during decades of space exploration at JPL, and celebrates the successes achieved. These books will serve to guide a new generation of scientists and engineers.

We would like to thank the Office of the Chief Scientist and Chief Technologist for their encouragement and support. In particular, we would like to acknowledge the support of Thomas A. Prince, former JPL Chief Scientist; Erik K. Antonsson, former JPL Chief Technologist; Daniel J. McCleese, JPL Chief Scientist; and Paul E. Dimotakis, JPL Chief Technologist.

Joseph H. Yuen, Editor-in-Chief
JPL Space Science and Technology Series
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Foreword

I am very pleased to commend the Jet Propulsion Laboratory (JPL) Space Science and Technology Series, and to congratulate and thank the authors for contributing their time to these publications. It is always difficult for busy scientists and engineers, who face the constant pressures of launch dates and deadlines, to find the time to tell others clearly and in detail how they solved important and difficult problems, so I applaud the authors of this series for the time and care they devoted to documenting their contributions to the adventure of space exploration.

JPL has been NASA's primary center for robotic planetary and deep-space exploration since the Laboratory launched the nation's first satellite, Explorer 1, in 1958. In the 50 years since this first success, JPL has sent spacecraft to all the planets except Pluto, studied our own planet in wavelengths from radar to visible, and observed the universe from radio to cosmic ray frequencies. Current plans call for even more exciting missions over the next decades in all these planetary and astronomical studies, and these future missions must be enabled by advanced technology that will be reported in this series. The JPL Deep Space Communications and Navigation book series captured the fundamentals and accomplishments of these two related disciplines, and we hope that this new series will expand the scope of those earlier publications to include other space science, engineering, and technology fields in which JPL has made important contributions.

I look forward to seeing many important achievements captured in these books.

CHARLES ELACHI, Director
Jet Propulsion Laboratory
California Institute of Technology

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Preface

Electric propulsion was first envisioned 100 years ago, and throughout most of the 20th century was considered the technology of the future for spacecraft propulsion. With literally hundreds of electric thrusters now operating in orbit on communications satellites, and ion and Hall thrusters both having been successfully used for primary propulsion in deep-space scientific missions, the future for electric propulsion has arrived.

The literature contains several books from the 1960s and numerous journal articles and conference papers published over the years discussing electric thruster concepts, benefits, physics, and technological developments. Much of this work has been based on empirical investigations and laboratory-based development programs of different thruster types. As such, the fundamental understanding of how these thrusters work has generally lagged behind the technological achievements and applications of electric thrusters in space.

The quest over the past 10 years to improve often technically mature thruster performance and significantly extend thruster life for applications in deep-space propulsion and satellite station-keeping requires a much deeper understanding of the physics of electric thrusters. The purpose of this book is to discuss and explain how modern ion and Hall thrusters work by describing the fundamental physics of these devices. This is a challenging task requiring a basic knowledge of plasma physics, ion accelerators, cathodes, electrical discharges, high voltage, gas dynamics, and many other technologies. As such, we rely heavily on physics-based models that are often greatly simplified compared to the complex two-dimensional and three-dimensional codes required to accurately predict the plasma dynamics that drive thruster performance, and ultimately determine their life. Work in this field is still progressing, and we hope this book will lead to further research and advances in our understanding of these surprisingly complex devices.

While this effort encompasses a large body of literature in the area of ion and Hall thrusters, it is based largely on the research and development performed at the Jet Propulsion Laboratory (JPL). Therefore, this book should not be considered an all-inclusive treatise on the subject of electric thrusters or a review of their development history, but rather one that delves into the basics of two of the more modern electric engines that are finding increasingly more applications, specifically ion and Hall thrusters, in an attempt to provide a better understanding of their principles.

DAN M. GOEBEL and IRA KATZ
March 2008

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We are greatly indebted to our colleagues at the Jet Propulsion Laboratory who both collaborated in the research and development of these thrusters and provided valuable comments and material for this manuscript. We gratefully acknowledge the many contributions of John Anderson, John Brophy, Richard Hofer, Kristina Jameson, Ioannis Mikellides, Timothy O'Donnell, James Polk, Thomas Randolph, J. Steven Snyder, and Richard Wirz. The research and development at JPL on ion and Hall thrusters has been supported through the years by NASA and the Jet Propulsion Laboratory, California Institute of Technology. The authors would also like to thank the developers and manufacturers of the flight thrusters described here for performance data and photographs of their thrusters. Finally, we would like to thank Joseph Yuen for his support in the preparation and publication of this book, and gratefully acknowledge the extensive and skillful efforts by Patricia Ehlers, Judi Dedmon, and Katherine Goebel in the editing and preparation of this book.

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Chapter 1
Introduction

Electric propulsion is a technology aimed at achieving thrust with high exhaust velocities, which results in a reduction in the amount of propellant required for a given space mission or application compared to other conventional propulsion methods. Reduced propellant mass can significantly decrease the launch mass of a spacecraft or satellite, leading to lower costs from the use of smaller launch vehicles to deliver a desired mass into a given orbit or to a deep-space target.

In general, electric propulsion (EP) encompasses any propulsion technology in which electricity is used to increase the propellant exhaust velocity. There are many figures of merit for electric thrusters, but mission and application planners are primarily interested in thrust, specific impulse, and total efficiency in relating the performance of the thruster to the delivered mass and change in the spacecraft velocity during thrust periods. While thrust is self-explanatory, specific impulse (Isp) is defined as the propellant exhaust velocity divided by the gravitational acceleration constant g, which results in the unusual units of seconds. The total efficiency is the jet power produced by the thrust beam divided by the electrical power into the system. Naturally, spacecraft designers are then concerned with providing the electrical power that the thruster requires to produce a given thrust, as well as with dissipating the thermal power that the thruster generates as waste heat.

In this book, the fundamentals of the ion and Hall thrusters that have emerged as leading electric propulsion technologies in terms of performance (thrust, Isp, and efficiency) and use in space applications will be presented. These thrusters operate in the power range of hundreds of watts up to tens of kilowatts with an Isp of thousands of seconds to tens of thousands of seconds, and they produce thrust levels typically of some fraction of a newton. Ion and Hall thrusters generally use heavy inert gases such as xenon as the propellant. Other propellant materials, such as cesium and mercury, have been investigated in the past, but xenon is generally preferable because it is not hazardous to handle and process, it does not condense on spacecraft components that are above cryogenic temperatures, its large mass compared to other inert gases generates higher thrust for a given input power, and it is easily stored at high densities and low tank mass fractions. Therefore, the main focus will be on xenon as the propellant in ion and Hall thrusters, although performance with other propellants can be examined using the basic information provided here.

1.1 Electric Propulsion Background

A detailed history of electric propulsion up to the 1950s was published by Choueiri [1], and information on developments in electric propulsion since then can be found in reference books, e.g., [2], and on various internet sites, e.g., [3]. Briefly, electric propulsion was first conceived by Robert Goddard [4] in 1906 and independently described by Tsiolkovskiy [5] in Russia in 1911. Several electric propulsion concepts for a variety of space applications were included in the literature by Hermann Oberth in Germany in 1929 and by Shepherd and Cleaver in Britain in 1949. The first systematic analysis of electric propulsion systems was made by Ernst Stuhlinger [6] in his book *Ion Propulsion for Space Flight*, published in 1964, and the physics of electric propulsion thrusters was first described comprehensively in a book by Robert Jahn [7] in 1968. The technology of early ion propulsion systems that used cesium and mercury propellants, along with the basics of low-thrust mission design and trajectory analysis, was published by George Brewer [8] in 1970. Since that time, the basics of electric propulsion and some thruster characteristics have been described in several chapters of textbooks published in the United States on spacecraft propulsion [9–12]. An extensive presentation of the principles and working processes of several electric thrusters was published in 1989 in a book by S. Grishin and L. Leskov [13 (in Russian)].

Significant electric propulsion research programs were established in the 1960s at the National Aeronautics and Space Administration (NASA) Glenn Research Center, Hughes Research Laboratories, NASA's Jet Propulsion Laboratory (JPL), and at various institutes in Russia to develop this technology for satellite station-keeping and deep-space prime propulsion applications. The first experimental ion thrusters were launched into orbit in the early 1960s by the U.S. and Russia using cesium and mercury propellants. Experimental test flights of ion thrusters and Hall thrusters continued from that time into the 1980s.

The first extensive application of electric propulsion was by Russia using Hall thrusters for station keeping on communications satellites [14]. Since 1971 when the Soviets first flew a pair of SPT-60s on the Meteor satellite, over 238 Hall thrusters have been operated on 48 spacecraft to date [15]. Japan launched the first ion thruster system intended for north–south station keeping on the communications satellite Engineering Test Satellite (ETS) VI in 1995 [16]. Although a launch vehicle failure did not permit station keeping by this system, the ion thrusters were successfully operated in space. The commercial use of ion thrusters in the United States started in 1997 with the launch of a Hughes Xenon Ion Propulsion System (XIPS) [17], and the first NASA deep-space mission using the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) ion thruster was launched in 1998 on Deep Space 1 [18]. Since then, Hughes/Boeing launched their second-generation 25-cm XIPS ion thruster system [19] in 2000 for station-keeping applications on the high-power 702 communications satellite [20]. The Japanese have successfully used ion thrusters to provide the prime propulsion for the Hayabusa asteroid sample return mission [21], and the European Space Agency (ESA) has used Snecma's PPS-1350-G Hall thruster on its SMART-1 mission to the moon [22]. The Russians have been steadily launching communications satellites with Hall thrusters aboard and will continue to use these devices for future station-keeping applications [15]. The first commercial use of Hall thrusters by a U.S. spacecraft manufacturer was in 2004 on Space Systems Loral's MBSAT, which used the Fakel SPT-100 [23]. Additional ion and Hall thruster launches are planned in the U.S. in the near future using thrusters produced by commercial vendors [24–26].

In the past 20 years, electric propulsion use in spacecraft has grown steadily worldwide, and advanced electric thrusters have emerged over that time in several scientific missions and as an attractive alternative to chemical thrusters for station-keeping applications in geosynchronous communication satellites. Rapid growth has occurred in the last 10 years in the use of ion thrusters and Hall thrusters in communications satellites to reduce the propellant mass for station keeping and orbit insertion. The U.S. and the Russians have now each flown well over a hundred thrusters in communications satellites, and will continue to launch more ion and Hall thrusters in the future. The use of these technologies for primary propulsion in deep-space scientific applications has also been increasing over the past 10 years. There are many planned launches of new communications satellites and scientific missions that use ion and Hall thrusters in the coming years as the acceptance of the reliability and cost benefits of these systems grows.

1.2 Electric Thruster Types

Electric thrusters are generally described in terms of the acceleration method used to produce the thrust. These methods can be easily separated into three categories: electrothermal, electrostatic and electromagnetic. Common EP thruster types are described in the following.

Resistojet

Resistojets are electrothermal devices in which the propellant is heated by passing through a resistively heated chamber or over a resistively heated element before entering a downstream nozzle. The increase in exhaust velocity is due to the thermal heating of the propellant, which limits the Isp to low levels (<500 s).

Arcjet

An arcjet is also an electrothermal thruster that heats the propellant by passing it though a high current arc in line with the nozzle feed system. While there is an electric discharge involved in the propellant path, plasma effects are insignificant in the exhaust velocity because the propellant is weakly ionized. The Isp is limited by the thermal heating to less than about 700 s for easily stored propellants.

Ion Thruster

Ion thrusters employ a variety of plasma generation techniques to ionize a large fraction of the propellant. These thrusters then utilize biased grids to electrostatically extract ions from the plasma and accelerate them to high velocity at voltages up to and exceeding 10 kV. Ion thrusters feature the highest efficiency (from 60% to >80%) and very high specific impulse (from 2000 to over 10,000 s) compared to other thruster types.

Hall Thruster

This type of electrostatic thruster utilizes a cross-field discharge described by the Hall effect to generate the plasma. An electric field established perpendicular to an applied magnetic field electrostatically accelerates ions to high exhaust velocities, while the transverse magnetic field inhibits electron motion that would tend to short out the electric field. Hall thruster efficiency and specific impulse is somewhat less than that achievable in ion thrusters, but the thrust at a given power is higher and the device is much simpler and requires fewer power supplies to operate.

Electrospray/Field Emission Electric Propulsion Thruster

These are two types of electrostatic electric propulsion devices that generate very low thrust (<1 mN). Electrospray thrusters extract ions or charged droplets from conductive liquids fed through small needles and accelerate them electrostatically with biased, aligned apertures to high energy. Field emission electric propulsion (FEEP) thrusters wick or transport liquid metals (typically indium or cesium) along needles, extracting ions from the sharp tip by field emission processes. Due to their very low thrust, these devices will be used for precision control of spacecraft position or attitude in space.

Pulsed Plasma Thruster

A pulsed plasma thruster (PPT) is an electromagnetic thruster that utilizes a pulsed discharge to ionize a fraction of a solid propellant ablated into a plasma arc, and electromagnetic effects in the pulse to accelerate the ions to high exit velocity. The pulse repetition rate is used to determine the thrust level.

Magnetoplasmadynamic Thruster

Magnetoplasmadynamic (MPD) thrusters are electromagnetic devices that use a very high current arc to ionize a significant fraction of the propellant, and then electromagnetic forces (Lorentz $\mathbf{J} \times \mathbf{B}$ forces) in the plasma discharge to accelerate the charged propellant. Since both the current and the magnetic field are usually generated by the plasma discharge, MPD thrusters tend to operate at very high powers in order to generate sufficient force for high specific impulse operation, and thereby also generate high thrust compared to the other technologies described above.

Some of the operating parameters of thrusters with flight heritage (resistojet, arcjet, ion, Hall, and PPT) are summarized in Table 1-1. There are many other types of electric propulsion thrusters in development or merely conceived that are too numerous to be described here. This book will focus on the fundamentals of electrostatic ion and Hall thrusters.

Table 1-1. Typical operating parameters for thrusters with flight heritage [30].

Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	2500–3600	0.4–4.3	40–80	Xenon
Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
PPTs	850–1200	<0.2	7–13	Teflon

1.3 Ion Thruster Geometry

An ion thruster consists of basically three components: the plasma generator, the accelerator grids, and the neutralizer cathode. Figure 1-1 shows a schematic cross section of an electron-bombardment ion thruster that uses an electron discharge to generate the plasma. The discharge cathode and anode represent the plasma generator in this thruster, and ions from this region flow to the grids and are accelerated to form the thrust beam. The plasma generator is at high positive voltage compared to the spacecraft or space plasma and, therefore, is enclosed in a "plasma screen" biased near the spacecraft potential to eliminate electron collection from the space plasma to the positively biased surfaces. The neutralizer cathode is positioned outside the thruster and provides electrons at the same rate as the ions to avoid charge imbalance with the spacecraft.

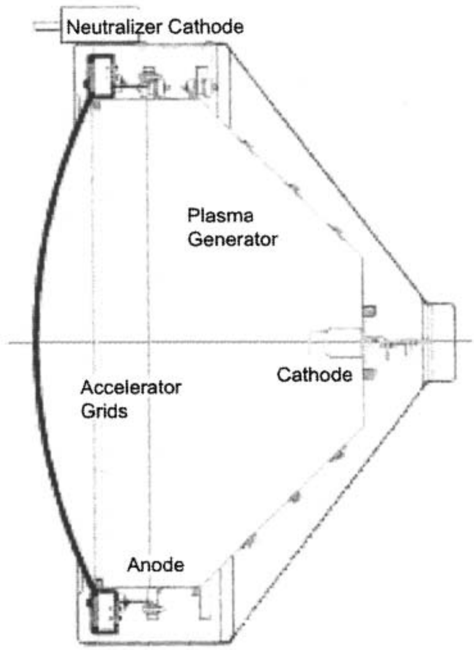

Fig. 1-1. Ion thruster schematic showing grids, plasma generator, and neutralizer cathode.

Ion thrusters that use alternative plasma generators, such as microwave or radio frequency (rf) plasma generators, have the same basic geometry with the plasma generator enclosed in a plasma screen and coupled to a gridded ion accelerator with a neutralizer cathode. The performance of the thruster depends on the plasma generator efficiency and the ion accelerator design. A photograph of a large, 57-cm-diameter ion thruster fabricated by JPL, called NEXIS [26], is shown in Fig. 1-2. This thruster is capable of operating at over 20 kW of power with an Isp exceeding 7000 s and a design lifetime of over 100,000 hours.

1.4 Hall Thruster Geometry

A Hall thruster can also be thought of as consisting of basically three components: the cathode, the discharge region, and the magnetic field

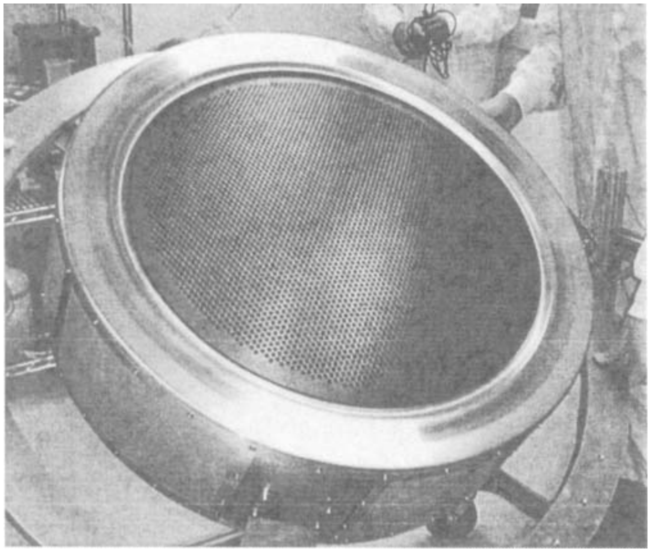

Fig. 1-2. Photograph of the NEXIS ion thruster [27] showing the 57-cm-diameter multiaperture grids and plasma screen enclosing the thruster body.

generator. Figure 1-3 shows a schematic cross section of a Hall thruster. In this example, a cylindrical insulating channel encloses the discharge region. Magnetic coils (not shown) induce a radial magnetic field between the center pole piece and the flux return path at the outside edge. The cathode of the discharge is an external hollow cathode, and the anode is a ring located at the base of the cylindrical slot shown. Gas is fed into the discharge channel through the anode and dispersed into the channel. Electrons attempting to reach the anode encounter a transverse radial magnetic field, which reduces their mobility in the axial direction and inhibits their flow to the anode. The electrons tend to spiral around the thruster axis in the $\mathbf{E} \times \mathbf{B}$ direction and represent the Hall current from which the device derives its name. Ions generated by these electrons are accelerated by the electric field from the anode to the cathode-potential plasma produced at the front of the thruster. Some fraction of the electrons emitted from the hollow cathode also leave the thruster with the ion beam to neutralize the exiting charge. The shape and material of the discharge region channel and the details of the magnetic field determine the performance of the thruster.

Figure 1-4 shows a photograph of an Aerojet BPT-4000 Hall thruster [25,26] that has completed qualification for flight. This thruster operates from 1 to 5 kW with an Isp near 2000 s and a total system efficiency of up to 52%. This

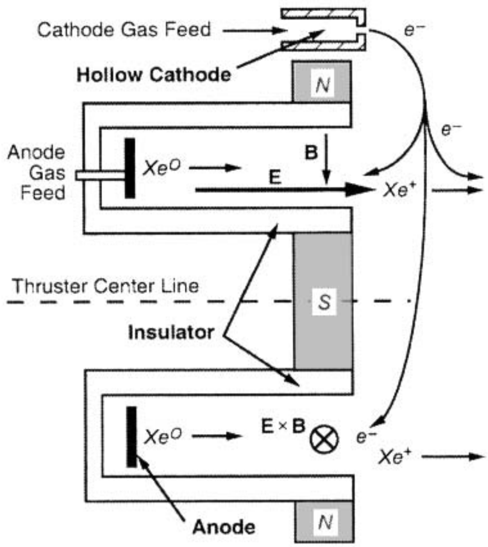

Fig. 1-3. Schematic illustration of a Hall thruster showing the radial magnetic field and the accelerating electric field.

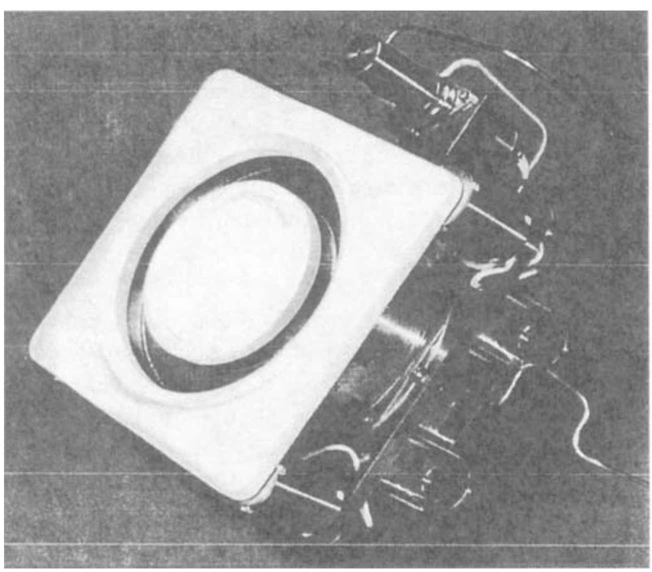

Fig. 1-4. Photograph of a BPT-4000 Hall thruster manufactured by Aerojet [25,26].

thruster is in development for satellite station-keeping and deep-space propulsion applications. The more familiar Russian SPT-100 Hall thruster, which has considerable flight heritage on Russian spacecraft [15] and is described in Chapter 9, operates nominally [28,29] at a power of 1.35 kW and an Isp of 1600 s. This thruster includes a redundant hollow cathode to increase the reliability and features a lifetime in excess of 9000 hours[12]. In addition, the SPT-100 has also been flown on U.S. commercial communications satellites [23].

1.5 Beam/Plume Characteristics

The ion beam exiting the thruster is often called the thruster plume, and the characteristics of this plume are important in how the exhaust particles interact with the spacecraft. Figure 1-5 shows the generic characteristics of a thruster plume. First, the beam has an envelope and a distribution of the ion currents in that envelope. Second, the energetic ions in the beam can charge exchange with neutral gas coming from the thruster or the neutralizer, producing fast neutrals propagating in the beam direction and slow ions. These slow ions then move in the local electric fields associated with the exit of the acceleration region and the neutralizer plasma, and can backflow into the thruster or move radially to potentially bombard any spacecraft components in the vicinity. Third, energetic ions are often generated at large angles from the thrust axis due either to edge effects (fringe fields) in the acceleration optics of ion thrusters, large gradients in the edge of the acceleration region in Hall thrusters, or scattering of the beam ions with the background gas. Finally, the thruster evolves impurities associated

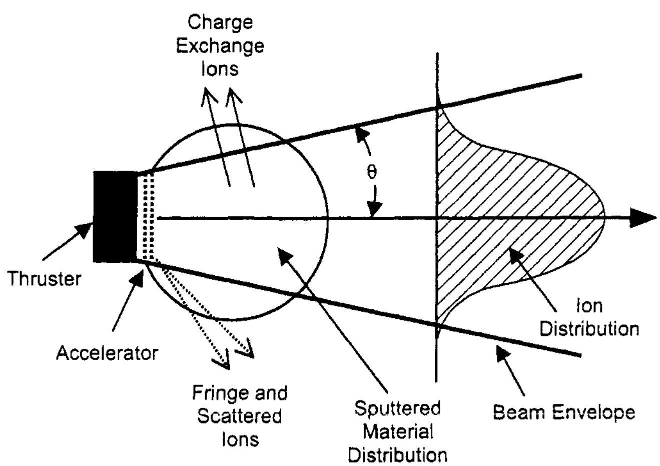

Fig. 1-5. Generic thruster-beam plume showing the ion distribution, sputtered material, and "large angle" or charge exchange ions.

with the wear of the thruster components. This can be due to the sputtering of the grids in ion thrusters, the erosion of the ceramic channel in Hall thrusters, or the evolution of cathode materials or sputtering of other electrodes in the engines. This material can deposit on spacecraft surfaces, which can change surface properties such as emissivity, transparency, etc.

The plume from a thruster typically has a complex structure. Figure 1-6 shows an exploded view of a calculated three-dimensional plume from a three-grid ion thruster. In this case, the ion beam is shown as the extended plume, and the molybdenum atom plume escaping through the third grid from sputter erosion of the center-accel grid is shown by the wider angular divergent dark plume and several beam lobes. Since the energetic ions tend to sputter surfaces that they come into contact with, and the metal atoms tend to deposit and coat surfaces they come in contact with, the net interaction of these plumes with the spacecraft is very different and must be examined with three-dimensional (3-D) codes of the spacecraft layout coupled to these types of thruster plume plots. Techniques and models for doing this are described in detail in Chapter 9,

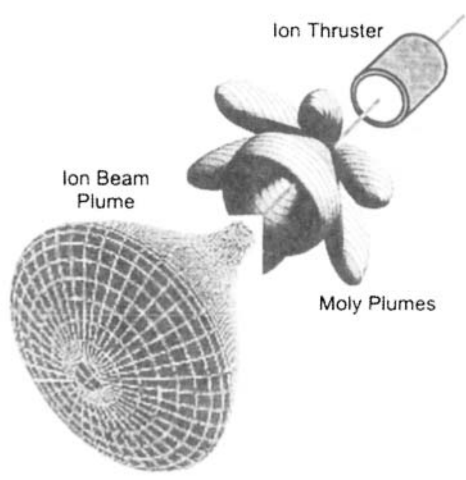

Fig. 1-6. Example of a 3-D plot of an ion thruster plume. Calculated and plotted by Dr. Thomas LaFrance, Manhattan Beach, California, 2007, and used here with permission.

References

[1] E. Y. Choueiri, "A Critical History of Electric Propulsion: The First 50 Years (1906-1956)," *Journal of Propulsion and Power*, vol. 20, pp. 193–203, 2004.

[2] R. G. Jahn and E. Y. Choueiri, "Electric Propulsion," *Encyclopedia of Physical Science and Technology*, third edition, vol. 5, New York: Academic Press, 2002.

[3] http://en.wikipedia.org/wiki/Field Emission_Electric_Propulsion

[4] R. H. Goddard, *The Green Notebooks*, vol. 1, The Dr. Robert H. Goddard Collection at the Clark University Archives, Clark University, Worchester, Massachusetts.

[5] T. M. Mel'kumov, ed., *Pioneers of Rocket Technology, Selected Works*, Academy of Sciences of the USSR, Institute for the History of Natural Science and Technology, Moscow, 1964; translated from the 1964 Russian text by NASA as NASA TT F-9285, 1965.

[6] E. Stuhlinger, *Ion Propulsion for Space Flight*, New York: McGraw-Hill, 1964.

[7] R. G. Jahn, *Physics of Electric Propulsion*, New York: McGraw-Hill, 1968.

[8] G. R. Brewer, *Ion Propulsion Technology and Applications*, New York: Gordon and Breach, 1970.

[9] H. R. Kaufman, "Technology of Electron-Bombardment Ion Thrusters," in *Advances in Electronics and Electron Physics*, vol. 36, edited by L. Marton, New York: Academic Press, 1974.

[10] P. J. Turchi, "Electric Rocket Propulsion Systems," Chapter 9 in *Space Propulsion Analysis and Design*, edited by R. W. Humble, G .N. Henry, and W. J. Larson, New York: McGraw-Hill, pp. 509–598, 1995.

[11] J. R. Wertz and W. J. Larson, eds., *Space Mission Analysis and Design*, third edition, New York: Springer Publishing Co., 1999.

[12] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*, New York: John Wiley and Sons, pp. 660–710, 2001.

[13] S. D. Grishin and L. V. Leskov, *Electrical Rocket Engines of Space Vehicles*, Moscow, Russia: Mashinostroyeniye Publishing House, 1989 (in Russian).

[14] A. S. Boever, V. Kiim, A. S. Koroteev, L. A. Latyshev, A. I. Morozov, G. A. Popov, Y. P. Rylov, and V. V. Zhurin, "State of the Works of Electrical Thrusters in the USSR," IEPC-91-003, 22nd International Electric Propulsion Conference, Viareggio, Italy, 1991.

[15] V. Kim, "Electric Propulsion Activity in Russia," IEPC-2001-005, 27th International Electric Propulsion Conference, Pasadena, California, October 14–19, 2001.

[16] S. Shimada, K. Sato, and H. Takegahara, "20-mN Class Xenon Ion Thruster for ETS-VI," AIAA-1987-1029, 19th International Electric Propulsion Conference, Colorado Springs, Colorado, May 11–13, 1987.

[17] J. R. Beattie, "XIPS Keeps Satellites on Track," *The Industrial Physicist*, June 1998.

[18] J. R. Brophy, "NASA's Deep Space 1 Ion Engine," *Review Scientific Instruments*, vol. 73, pp. 1071–1078, 2002.

[19] J. R. Beattie, J. N. Matossian, and R. R. Robson, "Status of Xenon Ion Propulsion Technology," *Journal of Propulsion and Power*, vol. 6, no. 2, pp. 145–150, 1990.

[20] D. M. Goebel, M. Martinez-Lavin, T. A. Bond, and A. M. King, "Performance of XIPS Electric Propulsion in Station Keeping of the Boeing 702 Spacecraft," AIAA-2002-4348, 38th Joint Propulsion Conference, Indianapolis, Indiana, July 7–10, 2002.

[21] H. Kuninaka, K. Nishiyama, I. Funakai, K. Tetsuya, Y. Shimizu, and J. Kawaguchi, "Asteroid Rendezvous of Hayabusa Explorer Using Microwave Discharge Ion Engines," 29th International Electric Propulsion Conference, IEPC-2005-010, Princeton, New Jersey, October 31–November 4, 2005.

[22] C. R. Koppel and D. Estublier, "The SMART-1 Hall Effect Thruster around the Moon: In Flight Experience," 29th International Electric Propulsion Conference, IEPC-2005-119, Princeton, New Jersey, October 31–November 4, 2005.

[23] D. J. Pidgeon, R. L. Corey, B. Sauer, and M. L. Day, "Two Years On-Orbit Performance of SPT-100 Electric Propulsion," AIAA-2006-5353, 24th AIAA International Communications Satellite Systems Conference, San Diego, California, June 11–14, 2006.

[24] K. R. Chien, W. G. Tighe, and S. Hart, "L-3 Communications ETI Electric Propulsion Overview," 29th International Electric Propulsion Conference, IEPC-2005-315, Princeton, New Jersey, October 31–November 4, 2005.

[25] F. Wilson, D. King, M. Willey, R. Aadland, D. Tilley, and K. deGrys, "Development Status of the BPT Family of Hall Current Thrusters," AIAA-99-2573, 35th Joint Propulsion Conference, Los Angeles, California, June 20–24, 1999.