

Chapter 1

Introduction

Electric propulsion (EP) is an in-space propulsion technology aimed at achieving thrust with high exhaust velocities, which results in a reduction in the amount of on-board propellant required for a given space mission or space propulsion 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 orbit or to a deep space target. Alternatively, the reduced propellant mass enabled using EP can be used to increase the delivered payload mass on a given launch vehicle.

In general, 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, propellant flow rate or specific impulse, and total efficiency in relating the performance of the thruster to the delivered mass and change in the spacecraft velocity (Δv) during thrusting periods. Although thrust is self-explanatory, specific impulse (Isp) is defined as the mean effective 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 required propellant flow, and in dissipating the thermal power that the thruster generates as waste heat.

In this book, the fundamentals of EP are presented. There is an emphasis on ion and Hall thrusters that have emerged as leading EP technologies in terms of performance (thrust, Isp, and efficiency) and use in space applications, but other thrusters such as electromagnetic thrusters are also described. Ion and Hall 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 produce thrust levels of a fraction of a Newton to over a Newton. Ion and Hall thrusters generally use heavy inert gases such as xenon or krypton as propellants, but other propellant materials, such as cesium and mercury, have been investigated in the past. 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 densities of about 1 g/cm^3 with low tank mass fractions. Krypton is also an emerging propellant that is cheaper than xenon and provides slightly higher Isp (due to its lower mass) than xenon for a given thruster electrical configuration. Electromagnetic thrusters can use nearly any propellant, but tend toward lower atomic mass to improve performance and Isp. However, this book will primarily focus on xenon as the propellant in ion and Hall thrusters, and performance with other propellants such as krypton can be examined using the information

provided here. The 2nd Edition of this book provides updates on the progress made in hollow cathode technology and ion and Hall thrusters since the 1st Edition, and includes new chapters on magnetically shielded Hall thrusters, electromagnetic thrusters, and future thruster concepts.

1.1 Electric Propulsion Background

A detailed history of EP up to the 1950s was published by Choueiri [1], and information on developments in EP since then can be found in reference books [2] and on various internet sites [3]. Briefly, EP was first conceived by Konstantin Tsiolkovsky [4] in Russia in 1903 and independently by Robert Goddard [5] in the United States in 1906 and Hermann Oberth in Germany [6] in 1929. Several EP concepts for some space applications were published in the literature by Shepherd and Cleaver in Britain in 1949. The first systematic analysis of EP systems was made by Ernst Stuhlinger [7] in his book *Ion Propulsion for Space Flight* published in 1964, and the physics of EP thrusters was first described comprehensively in the book by Robert Jahn [8] 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 [9] in 1970. Since that time, the basics of EP and some thruster characteristics have been described in several chapters of textbooks published in the US on spacecraft propulsion [10–13]. 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 [14] (in Russian). A survey of the early flight history of ion propulsion projects in the US was published by J. Sovey et al. [15] in 1999.

Significant EP research programs were established in the 1960s at NASA's Glenn Research Center (GRC), Hughes Research Laboratories (HRL), 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 electric thrusters were launched into orbit in the early 1960s [15] by the United States (US) and by Russia. The US demonstrated the first extended operation of ion thrusters in orbit with the Space Electric Rocket Test (SERT-II) mission [16] launched in 1970. The SERT-II mercury ion thrusters were also the first to use a hollow cathode "plasma-bridge neutralizer" to provide complete ion beam neutralization in space. Experimental test flights of ion thrusters and Hall thrusters continued from that time into the 1990s.

A detailed description of flight electric thrusters, with performance information and photos, is given in Chapter 12. Briefly, the first extensive application of EP was by Russia using Hall thrusters for station keeping on weather and communications satellites [17]. Since 1971, when the Soviets first flew a pair of SPT-60s on the Meteor satellite, over 250 SPT Hall thrusters have been operated on dozens of satellites to date [18]. Japan launched the first ion thruster system intended for north-south station keeping on the communications satellite "Engineering Test Satellite (ETS) VI" in 1995 [19]. However, a launch vehicle failure did not permit station keeping by this system, but the ion thrusters were successfully operated in space. The first commercial use of ion thrusters in the United States started in 1997 with the launch of a Hughes Xenon Ion Propulsion System (XIPS) [20], and the first NASA deep space mission using the NSTAR ion thruster was launched in 1998 on Deep Space-1 [21]. Since then, Hughes/Boeing launched their second generation 25-cm XIPS ion thruster system [22] in 2000 for station keeping applications on the high power 702 communications satellite [23]. The Hughes/Boeing 702 spacecraft is the first satellite to use electric thrusters for all propulsion applications (orbit raising, station keeping, momentum management, and attitude control).

The Japanese Space Agency (JAXA) successfully used the $\mu 10$ ion thrusters to provide the prime propulsion for the Hayabusa asteroid sample return mission [24] launched in 2003, and an

upgraded version of this microwave ion thruster [25] was used for prime propulsion on Hayabusa-2 launched in 2014. The European Space Agency (ESA) used the Safran manufactured PPS-1350-G Hall thruster on its SMART-1 mission to the moon [26] also in 2003. The Russians have been steadily launching communications satellites with Hall thrusters aboard since 1971, and will continue to use these devices in the future for station keeping applications [18]. The first commercial use of Hall thrusters by a US spacecraft manufacturer was in 2004 on Space Systems Loral's (SSL) MBSAT, which used the Fakel SPT-100 [27]. ESA launched the QinetiQ/UK T5 ion thruster on the GOCE mission [28] in 2009. This was followed in 2010 with the launch of Aerojet's BPT-4000 Hall thruster [29] (now called the XR-5) on the AF/LMC AEHF satellite. ESA launched the QinetiQ manufactured T6 ion thruster [30] on the BepiColombo mission to Mercury in 2018. SSL launched its first spacecraft that used the 4.5 kW Fakel SPT-140 Hall thruster [31] in 2018 for orbit raising and station keeping. The first spacecraft that did not utilize any chemical propulsion (no kick-stage thruster for orbit insertion or chemical thrusters for orbit maintenance) was the Boeing's "all-electric" 702SP satellite [32] launched in 2015. NASA/GRC's NEXT ion thruster was flight demonstrated in 2021 on the DART mission [33]. Additional ion and Hall thruster launches are ongoing now for emerging LEO communications constellations, such as the thousands of SpaceX Starlink launches each with a Hall thruster used for orbit insertion and station keeping. This trend will continue going forward using various thrusters produced by commercial vendors, with Hall thrusters dominating the present market.

In the past 25 years, EP use in spacecrafts has grown steadily worldwide [34, 35], and advanced electric thrusters have emerged [36] for scientific missions and as a competitive alternative to chemical thrusters for station keeping and orbit raising applications in geosynchronous communication satellites. Rapid growth has occurred in the last 10 years in the use of ion thrusters and Hall thrusters in commercial communications satellites to reduce the propellant mass for station keeping and orbit insertion. The US, Europeans, and the Russians have now flown thousands of electric thrusters on 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 15 years. There are many planned launches of new EP spacecraft, especially for the emerging LEO communications constellations and for challenging scientific missions, that use ion and Hall thrusters as the acceptance of the reliability and cost benefits of these systems grow.

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. Electrothermal thrusters are not discussed in this book, except for a brief description below, because the technology is very mature and covered in previous books [8], and the performance is relatively low compared to other types of electric thrusters. Common electric thruster types are:

1.2.1 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).

1.2.2 Arcjet

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

1.2.3 Electropray/FEED Thruster

These are two types of electrostatic EP devices that generate very low thrust (<1 mN). Electropray 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 (FEED) thrusters transport liquid metals (typically indium or cesium) along needles, extracting ions from a “Taylor-cone” on the sharp tip by field emission processes. Owing to their very low thrust, these devices are used primarily for precision control of spacecraft position or attitude in space, but are now being pursued for CubeSat and small sat applications. Electropray/FEED thrusters are not discussed further in this edition because a book specifically on micropropulsion thrusters has previously been published [37].

1.2.4 Ion Thruster

Ion thrusters employ a variety of plasma generation techniques (DC discharge, rf discharge, microwave discharge, arcs, etc.) to ionize a large fraction of a gaseous propellant. These thrusters then utilize biased grids to electrostatically extract ions from the plasma and accelerate them to high velocity by voltages typically ranging from 1 to 2 kV, but which can even exceed 10 kV in laboratory thrusters. A hollow cathode positioned external to the thruster and grids provides electrons to neutralize the beam. Ion thrusters feature the highest efficiency (60 to >80%) and very high-specific impulse (2000 to over 10,000 s) compared to other thruster types.

1.2.5 Hall Thruster

This type of thruster utilizes an $\mathbf{E} \times \mathbf{B}$ cross-field discharge described by the Hall effect to generate the plasma. An electric field is established perpendicular to an applied radial magnetic field to electrostatically accelerate ions to high exhaust velocities. The transverse magnetic field causes the electrons to move in cycloidal orbits around an axisymmetric discharge channel (the “Hall current”), and inhibits electron motion axially toward the anode to create a resistivity in the plasma that supports the ion accelerating electric field. Although the force is transferred from the ions to the thruster through the magnetic field, these are classified here as electrostatic thrusters because the unmagnetized ions are accelerated electrostatically. Hall thruster efficiency and specific impulse is typically somewhat less than that achievable in ion thrusters, but the thrust at a given power is higher, the power density is higher, and the device is much simpler and requires fewer power supplies to operate. Recently, advanced Hall thrusters have begun utilizing a more complex magnetic field shape near the discharge channel exit called “Magnetic Shielding” that eliminated wall erosion and enabled Hall thrusters with lifetimes in excess of 50,000 h.

1.2.6 Magnetoplasmadynamic (MPD) Thruster

These electromagnetic devices use a very high current arc to ionize a significant fraction of the propellant, and then use 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 currents and high powers to generate sufficient force and thereby also generate high thrust compared to the other technologies described above. Since MPD thrusters tend to run at lower discharge voltages (<100 V) to avoid significant electrode erosion, they tend to use light atoms as propellant (H_2 , Li and Ar) to achieve longer life at higher Isp.

1.2.7 Pulsed Plasma Thruster (PPT)

A PPT is an electromagnetic thruster that utilizes a pulsed discharge to ionize a fraction of a solid propellant ablated by a plasma arc, and then uses the electromagnetic Lorentz $\mathbf{J} \times \mathbf{B}$ force generated in the pulsed plasma to accelerate the ions to high exit velocity. PPTs that produce the order 1 mN of thrust at an Isp of over 1000 s have been flown at an average input power of about 100 W. The discharge pulse is short (tens of μsec) to avoid arc damage, and the repetition rate is typically used to determine the average thrust level.

1.2.8 Pulsed Inductive Thruster (PIT)

Like the PPT, the PIT is another electromagnetic thruster that operates in pulsed mode. However, its operational principle is distinctly different making it truly unique among all other mainstream electromagnetic thrusters. For example, the Lorentz force is produced inductively and, therefore, the PIT does not require electrodes. Also, in principle, it can operate with a wide range of gaseous propellants, although a single-shot operation has shown optimal performance with polyatomic molecule fuels. For example, a PIT operating with ammonia at 4.6 kJ per pulse demonstrated nearly constant efficiencies exceeding 50% at the range of specific impulse $4000 \text{ s} < \text{Isp} < 8000 \text{ s}$. Its propensity to work best with such polyatomic fuels renders the thruster as a potentially ideal candidate for a water-propellant operation.

Some of the operating parameters of chemical and electric thrusters, most with flight heritage, are summarized in Table 1-1. There are many other types of EP thrusters in development or merely conceived that are too numerous to be described here, some of which are described in Chapter 10. This book will focus on the fundamentals of electrostatic and electromagnetic thrusters as outlined in the next section.

Table 1-1 Typical parameters for selected thrusters [34, 35, 38].

Thruster	Specific impulse (sec)	Thrust	Input power (kW)	Efficiency range(%)	Propellant
Cold gas	25–75	0.1–100 N	–	–	Various
Solid chemical	250–304	10^7 N	–	–	Various
Liquid chemical (monopropellant)	150–235	1–500 N	–	–	N_2H_4 H_2O_2
Liquid chemical (bipropellant)	274–467	10^7 N	–	–	Various
Resistojet	100–300	0.5–6000 mN	0.1–1	65–90	N_2H_4 monoprop
Arcjet	130–600	50–6800 mN	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	2500–4000	0.1–750 mN	0.4–4.5	40–83	Xe, Kr
Hall thruster	1500–3000	0.1–2000 mN	1.5–4.5	35–70	Xe, Kr
PPT	850–1200	0.05–10 mN	<0.2	3–30	Teflon
MPD	200–3200	0.1–2000 mN	<1	20–60	H_2 , Li, Ar, Xe

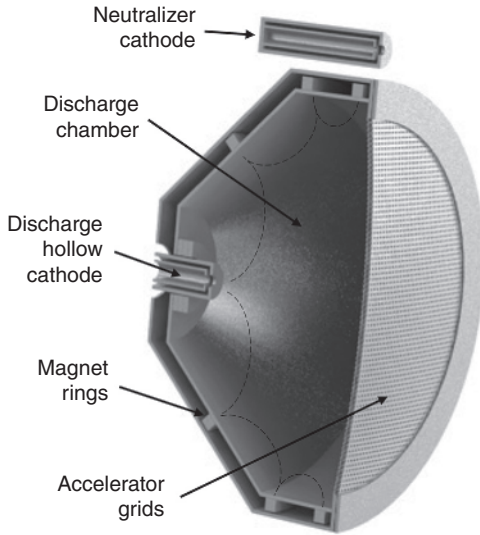


Figure 1-1 Ion thruster schematic showing grids, plasma generator and neutralizer cathode.

1.3 Electrostatic Thrusters

1.3.1 Ion Thrusters

An ion thruster consists of basically three components: the plasma generator, 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 with a magnetic field produced by permanent magnets at the surface of the anode to generate the plasma. The discharge from the cathode to the anode generates the plasma in this thruster, and ions from the discharge chamber 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 so 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 in the beam to avoid charge imbalance with the spacecraft.

A photograph of the NEXT ion thruster developed at NASA/GRC [39] is shown in Fig. 1-2. This thruster is capable of operating at 0.5–6.9 kW with a maximum I_{sp} of 4000 s. Ion thrusters that use



Figure 1-2 Photograph of the NEXT ion thruster during thermo-vac testing at JPL (Source: NASA/JPL, Public Domain).

alternative plasma generators, such as microwave or 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.

1.3.2 Hall Thrusters

A Hall thruster can also be thought of as consisting of basically three components: the cathode, the discharge region, and the magnetic field 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 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 internal centrally mounted hollow cathode, although external cathodes mounted outside the thruster body are also used. The anode is a ring with some structure to evenly distribute the propellant gas in the annular channel, and is located at the base of the cylindrical discharge channel. 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 a SPT-100 Hall that has extensive flight experience on Russian communications satellites [17]. This thruster, described in Chapter 12, has redundant externally mounted hollow cathodes and operates nominally [40] at a power of 1.35 kW and an Isp of 1600 s. The thruster includes a redundant hollow cathode to increase the reliability and features a lifetime in excess of 9000 h. The SPT-100 has also been flown on US commercial communications satellites [27].

1.4 Electromagnetic Thrusters

There are many concepts for electromagnetic thrusters, but describing a couple of the more mature examples will illustrate the basic configuration. A more detailed description is contained in Chapter 9.

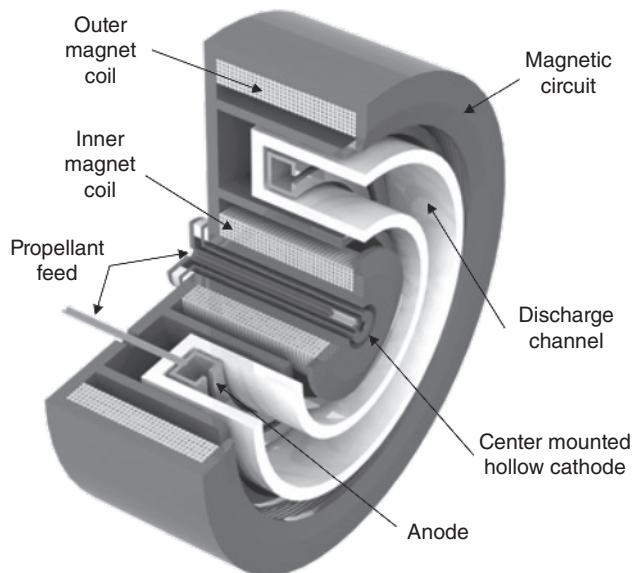


Figure 1-3 Illustration of a Hall thruster showing the annular discharge channel, magnetic circuit, anode and hollow cathode.



Figure 1-4 Photograph of the SPT-100 Hall thruster (*Source: [27]/American Institute of Aeronautics and Astronautics, Inc.*).

1.4.1 Magnetoplasmadynamic Thrusters

Magnetoplasmadynamic (MPD) thrusters [8] are high-power devices that produce thrust using the Lorentz electromagnetic force. The basic configuration consists of a centrally mounted cathode, a cylindrical or conical anode isolated from the center cathode, and for applied field thrusters magnetic field coils positioned outside the anode. Figure 1-5 shows an illustration of a typical MPD

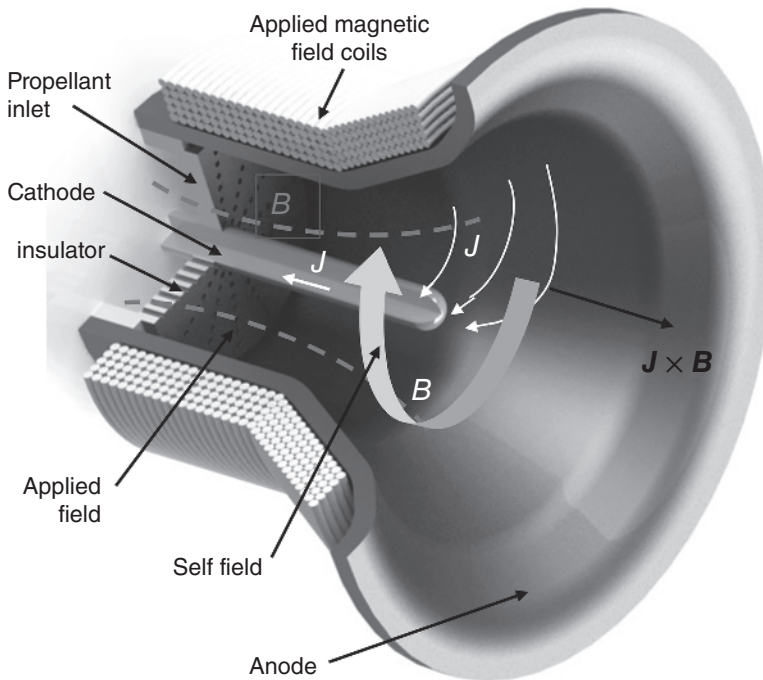


Figure 1-5 Illustration of an MPD thruster that includes applied magnetic field coils.

thruster design with these components. The cathode can consist of a refractory metal rod as shown in the figure, an assembly of refractory metal rods for more current capability, or a hollow cathode configuration, depending on the discharge current and cathode life desired. Current flowing in the cathode generates a “self-field” azimuthal magnetic field, and the radial component of the discharge current to the anode interacting with this azimuthal magnetic field generates axial thrust from the Lorentz force. This generation of transverse magnetic fields and plasma currents are inherent to all of the electromagnetic thruster concepts that use the Lorentz force to generate thrust.

In MPD thrusters with external coils, the “applied” magnetic field contributes to the Lorentz force and changes the plasma structure near the anode. There are also other forces on the plasma due to the complex structure of the magnetic fields and the current distributions, which are described in Chapter 9. MPD thrusters typically run in the multi-kiloamp, tens to hundreds of kilowatts power range, and scale well to over a megawatt in a compact, high-power package. An example of a laboratory self-field MPD thruster is shown in Fig. 1-6. There has been extensive research and development internationally on MPD thrusters, but to date only technology demonstration pulsed MPDs have been flown in space.



Figure 1-6 Example of a laboratory self-field MPD thruster (Source: Photo credit: E. Choueiri, Princeton University).

1.4.2 Pulsed Plasma Thrusters

The first electric thruster to provide spacecraft attitude control in space was an electromagnetic pulsed plasma thruster (PPT). This thruster concept uses an arc discharge across two electrodes that ablates and vaporizes solid propellant feed into a channel. The transverse plasma current in the arc and the induced magnetic field produces a $\mathbf{J} \times \mathbf{B}$ force that generates thrust out of the system. Figure 1-7 shows a simple schematic of a PPT thruster, and Fig. 1-8 shows a photograph of the PPT that flew on the Earth Observing (EO-1) Mission in 2000 [41]. PPTs are inherently pulsed devices to avoid damage to the electrodes and generate the desired amount of propellant into the system, and produce the order of 1 mN of thrust at an Isp of over 1000 s with an average input power of the order of 100 W. PPTs are now a commercial product and have flown recently in microsatellite applications.

1.4.3 Pulsed Inductive Thrusters

Finally, pulsed inductive thrusters (PIT) [42, 43] are electromagnetic accelerators in which energy is stored capacitively and discharged through an inductive coil. First, the propellant is transiently puffed onto the surface of the induction coil followed by the

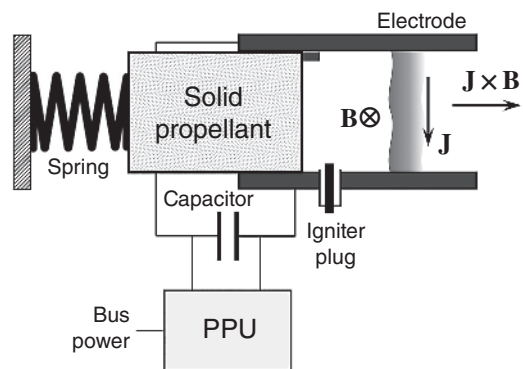


Figure 1-7 Simplified schematic of a PPT thruster.

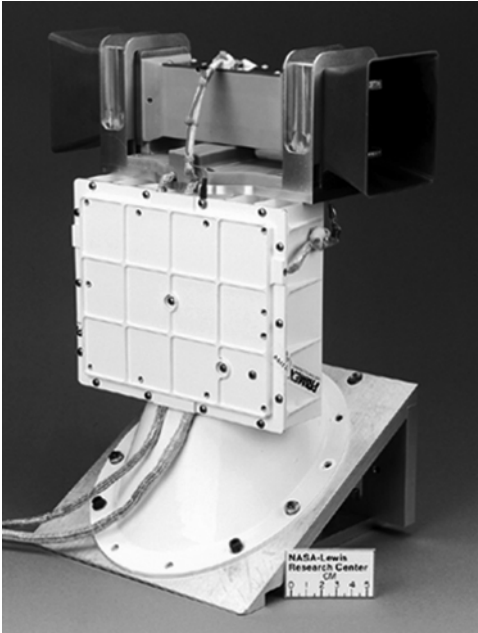


Figure 1-8 Photograph of the dual-direction PPT thruster and supporting electronics package flown on EO-1 (Source: NASA GRC, Public Domain).

release of the energy stored in the capacitors. The strong azimuthal electric field produced in this manner breaks down the propellant and establishes an azimuthal current that interacts with the rising radial magnetic field to accelerate the plasma along the thruster axis to high exhaust velocities. Such inductive acceleration, illustrated in Fig. 1-9, avoids the need for electrodes, the erosion of which has typically been the life-limiting process of traditional electromagnetic thrusters. Another unique benefit of the PIT is that it can potentially operate and perform well with any propellant, including water. Single-shot operation has demonstrated optimum performance with polyatomic molecule fuels such as ammonia which is plentiful and easily stored. Moreover, this thruster can maintain constant I_{sp} and thrust efficiency over a wide range of input power by varying the pulse rate to maintain a constant discharge energy per pulse. PITs can also have a high energy per pulse, and by increasing the pulse rate they can operate at very high power levels producing high thrust from a single thruster. The first laboratory investigations of this accelerator were, in

fact, performed in the late 1960s at Thompson Ramo Wooldridge Inc. (TRW) and continued later at Northrop Grumman Space Technology in the 1980s and 1990s [45]. It was not until the emergence of a renewed interest in high power EP in the early 2000s, however, that those largely

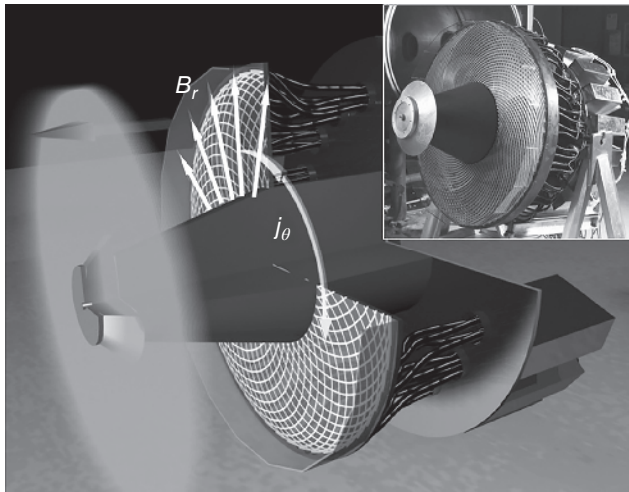


Figure 1-9 Schematic of the thruster illustrating the acceleration of a thin layer of ionized propellant by the interaction of the radial magnetic field and the induced azimuthal current, and a photograph (top right) of a PIT called the "Mark Va" developed at TRW Space & Technology Group (Source: [44]/AIP Publishing LLC).

empirical investigations were complemented by more in-depth analytical modeling and the first detailed 2-D numerical simulations [44, 46].

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 1-10 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 either due 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 with the wear of the thruster components. This can be caused by 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 an electric thruster typically has a complex structure. For example, Fig. 1-11 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 of high-angle particle fluxes. Likewise, Hall

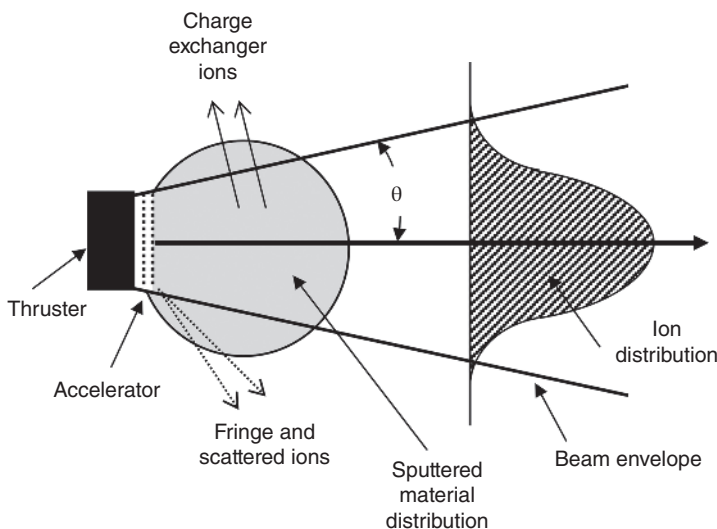


Figure 1-10 Generic thruster beam plume showing the ion distribution, sputtered material and “large angle” or charge exchange ions.

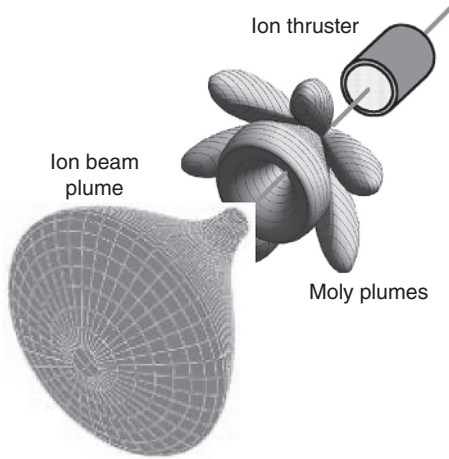


Figure 1-11 Example of a 3-D plot of an ion thruster plume (Source: [47]/Dr. Thomas LaFrance).

thruster plumes start from a conical discharge channel and merge downstream to form the thrust beam, and are characterized by a larger angular divergence of high-energy ions than typical from ion thrusters. Since the energetic ions in the thruster plume tend to sputter surfaces that they come into contact with, and metal or impurity atoms from the thruster tend to deposit and coat surfaces they come in contact with, the net interaction of these plumes with the spacecraft is very different from that encountered when using on-board chemical propulsion systems, and the spacecraft interactions must be examined with 3-D codes that include the spacecraft layout coupled to these types of thruster plume plots. Techniques and models for doing this are described in detail in Chapter 11.

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