INTRODUCTION TO ROCKET PROPULSION

L9: Introduction to Electric Propulsion

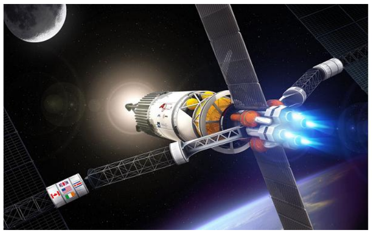

Figure 1: A spacecraft powered by electric rockets.

Why do we need electrically powered rocket engines?
In this lecture, we will investigate why we need electrically powered rockets to explore the Solar System! We learned in Lecture 4 that Solar System exploration requires high delta-v maneuvers. Chemical rockets, with their limited specific impulse, require significant amounts of propellant to complete high delta-v missions. In contrast, electrically powered rockets have high specific impulse, which makes them suitable for high delta-v missions and thus Solar System exploration. However, there is limited electrical power available on board a spacecraft, so electric thrusters are limited to low thrust operation. They are fired continuously over long periods of time to build up the velocity of a spacecraft. We'll survey the various types of electric thrusters and discuss their similarities and differences.

LEARNING GOALS:

1. Explain why chemical rockets are not suitable for high delta-v missions and use calculations to support your argument.
2. Calculate the velocity of a charged particle accelerated through an electric potential difference.
3. Use the Ideal Rocket Equation to compare and contrast the performance of chemical rockets and electric thrusters.
4. Explain why electric thrusters produce low thrust and compute the maximum thrust for a given amount of electric power.
5. Name the two major types of electric thrusters and describe their similarities and differences.

MOTIVATION FOR ELECTRIC PROPULSION

The last three lectures focused on chemical propulsion. We learned that chemical rockets use chemical propellants to create hot combustion gases that are accelerated to high velocities using a nozzle. Chemical rockets can produce A LOT of thrust! They are powerful enough to deliver astronauts, satellites, and spacecraft from Earth's surface into Earth orbit. We also learned that chemical rockets can operate both in the vacuum of outer space and within Earth's atmosphere. Chemical rockets seem really great, so why bother developing a completely different propulsion technology?

The Limitations of Chemical Propulsion

Chemical rockets have limitations which make them unsuitable for certain types of in-space missions. We know that chemical rockets produce significant amounts of thrust. Recall that the thrust of a rocket is proportional to the mass flow rate times the velocity of the exhaust (ignoring the pressure forces). The exhaust velocity of a chemical rocket is strongly dependent on the properties of the combustion reaction. In Lecture 6, we learned that the exhaust velocity is limited by the amount of chemical energy stored in the propellants. Because the exhaust velocity of chemical rockets is limited, high mass flow rates are used to achieve high thrust.

Chemical rockets are really interesting because they don't require an external power source. All of the energy used to accelerate the exhaust gases is stored in the bonds of the chemical propellants. However, this is a double-edged sword. On the one hand, we can design high-power chemical rockets without concern for budgeting additional mass for a power supply. On the other hand, having all the energy stored in the chemical propellants means that there is a finite supply of energy to produce thrust. Unfortunately, you can't add more energy, from an external source, to further accelerate the exhaust of a chemical rocket, at least in a practical way.

Chemical propulsion is therefore inherently limited in performance. In particular, the specific impulse of chemical rockets is constrained by several factors. First, the chemical energy available in the propellants is limited. Second, the maximum allowable chamber temperature is limited because there are few, if any, types of metals available to withstand high temperatures. Third, there are unavoidable energy losses that occur during the process of creating and accelerating the combustion gases. Some examples include incomplete combustion reactions, heat transfer from the combustion gases to the engine structure, and shock waves in the nozzle, which can reduce the energy of the exhaust gases.

Recall our previous example in which we estimated the specific impulse for a stoichiometric LOX-LH_2 reaction under ideal conditions. We found that the highest possible specific impulse was around 500 s. LOX-LH_2 is the most energetic combustion reaction used in rockets today, which means that our estimate is the best possible specific impulse for chemical rockets. In reality, the highest performing chemical rocket engine ever constructed, the Space Shuttle Main Engine (SSME), has a specific impulse of 450 s in vacuum.

Why do we need rocket technologies that yield a higher exhaust velocity and thus a higher specific impulse? Exploring the Solar System requires significant changes in velocity, typically on the order of 10,000 m/s or more. We call these, "high delta-v missions". Remember that the Ideal Rocket Equation tells us the higher the delta-v, the more propellant required. The amount of propellant needed to complete a particular change in velocity can be reduced if we use a rocket engine with high specific impulse. If we used chemical rockets for a high delta-v mission, the required propellant fraction would be so large that the mission would not be feasible!

Example 1:

Let's consider an example. Assume that we need to change the velocity of a spacecraft by 15,000 m/s. The chemical rocket engines used on spacecraft have low specific impulse, approximately 200-250 s. Remember that they can only use storable propellants, which produce less energetic chemical reactions. Also, the complex machinery that make the rocket engines on launch vehicles so efficient is too massive for spacecraft. Instead, less complex, less efficient systems are used to reduce the total mass of the propulsion system.

If the specific impulse of the spacecraft's rockets is 250 s, what percentage of the spacecraft mass needs to be propellant?

Let's use the Ideal Rocket Equation:

$$\begin{aligned}\frac{m_p}{m_0} &= 1 - \exp\left(-\frac{\Delta v}{g I_{sp}}\right) \\ &= 1 - \exp\left(-\frac{15{,}000\,\mathrm{m/s}}{(9.81\,\mathrm{m/s^2})(250\,\mathrm{s})}\right) \\ &= 0.998\end{aligned} \tag{1.1}$$

The spacecraft mass must be 99.8% propellant! This means that the structure and payload can only account for 0.2% of the spacecraft mass. High delta-v missions in space are not very feasible with chemical propulsion! Are rockets powered by electricity a better choice for such missions? Let's find out!

Note: We accept high propellant mass fractions (90% or more) for launch vehicles because chemical rockets are our only way to get to space. Once we're in space, we have the option to use electric propulsion.

Theoretical Performance of an Electric Rocket

Electric propulsion (EP) uses electrical energy to accelerate charged particles, such as atomic or molecular ions, to high velocities. Electric thrusters need an external power supply, which can come from batteries, fuel cells, solar arrays, or even nuclear reactors. We can provide however much energy we want to the thruster as long as we have a large enough power supply. The more energy we supply to the thruster, the faster the ions exit the thruster, which means higher specific impulse.

Thruster? Engine? Which word do we use?! "Engine" is typically used to describe chemical rockets whereas "thruster" is typically used to describe electrically powered rockets.

How fast can we accelerate ions using electrical energy? Let's use the conservation of energy to find out! The electrical potential energy, $\mathrm{U_e}$, of a charged particle is given by the following expression:

$$\mathrm{U_e} = q\phi \tag{1}$$

where q is the charge of the particle and ϕ is the value of the electric potential at the location of the particle. The charge of the particle can be positive or negative and is measured in Coulombs. The electric potential is measured in volts.

Let's assume that the total energy of the ion is given by the sum of its kinetic energy and electric potential energy:

$$\begin{aligned} \mathrm{E} &= \mathrm{KE} + \mathrm{U_e} \\ &= \frac{1}{2}mv^2 + q\phi \end{aligned} \tag{2}$$

where m is the mass of the ion and v is its velocity. By the conservation of energy, the total energy of the ion must be constant. Therefore, if we start an ion at rest in a region of high electric potential energy, the ion will be accelerated as it moves towards a region of lower electric potential energy. This is just like rolling a ball down a hill, but with electricity instead of gravity.

How do we create an electric potential difference? We can use two metal plates connected by a battery, as shown in Figure 2. The plate on the left has an electric potential equal to ϕ_0. The plate on the right has an electric potential of ϕ_f. The potential difference is $\Delta\phi = \phi_0 - \phi_f$. In this example, we'll assume that the ion is positively charged and that $\phi_f < \phi_0$. If we place the ion at the left plate and let it go, it will feel a force pulling it towards the plate on the right (we'll learn more about electrical forces next lecture).

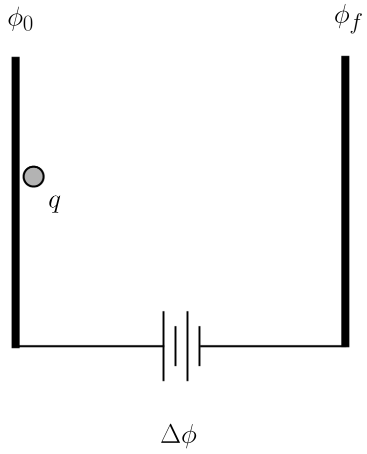

Figure 2: Two metal plates connected by a battery create an electric potential difference of $\Delta\phi = \phi_0 - \phi_f$. If $\Delta\phi > 0$, a positive ion will be accelerated from the left plate to the right plate.

For now let's focus on the energy exchange. Assuming the initial velocity of the ion is $v_0 = 0$ m/s, it's initial energy is:

$$\begin{aligned} E_0 &= \frac{1}{2}m{v_0}^2 + q\phi_0 \\ &= q\phi_0 \end{aligned} \tag{3}$$

The final energy of the ion when it reaches the plate on the right is:

$$E_f = \frac{1}{2}m{v_f}^2 + q\phi_f \tag{4}$$

Now let's apply the conservation of energy:

$$\begin{aligned} E_0 &= E_f \\ q\phi_0 &= \frac{1}{2}m{v_f}^2 + q\phi_f \end{aligned} \tag{5}$$

We can solve for the final velocity, v_f, of the ion:

$$\begin{aligned} v_f &= \sqrt{\frac{2q(\phi_0 - \phi_f)}{m}} \\ &= \sqrt{\frac{2q(\Delta\phi)}{m}} \end{aligned} \tag{6}$$

Notice that the larger the electric potential difference, $\Delta\phi$, the higher the final ion velocity.

> **Example 2:**
>
> Let's compare the performance of chemical and electrically powered rockets. The maximum specific impulse is 450 s for a chemical rocket that produces water vapor from liquid hydrogen and liquid oxygen. What if we used electrical energy to accelerate a water ion? Let's calculate the electric potential difference, measured in volts, that we would need to accelerate a water ion to the same velocity as the exhaust of a chemical rocket.
>
> The exhaust velocity of the chemical rocket is:
>
> $$\begin{aligned} v_f &= gI_{sp} \\ &= (9.81\,\mathrm{m/s^2})(450\,\mathrm{s}) \\ &= 4415\,\mathrm{m/s} \end{aligned} \tag{2.1}$$

Now let's solve for the electric potential difference. For a singly charged water ion, the mass is 18 amu and the charge is $e = 1.602 \times 10^{-19}$ C. We can solve equation 7 for $\Delta\phi$:

$$\begin{aligned}\Delta\phi &= \frac{m{v_f}^2}{2q} \\ &= \frac{(18\,\mathrm{amu})(1.66 \times 10^{-27}\,\mathrm{kg/amu})(4415\,\mathrm{m/s})^2}{2(1.602 \times 10^{-19}\,\mathrm{C})} \qquad (2.2) \\ &= 1.8\,\mathrm{volts}\end{aligned}$$

Only 1.8 volts are needed to accelerate a water ion to the exhaust velocity of a chemical rocket. A single AA battery can supply that voltage! On board a spacecraft, electrical power supplies can provide thousands of volts to an electric thruster. Let's estimate the specific impulse of a realistic electric thruster in the next example.

Example 3:

What is the final velocity of a water ion accelerated by 1000 volts? What is the theoretical specific impulse and how much propellant would such a rocket need to complete a $\Delta v = 15,000\,\mathrm{m/s}$ mission?

Let's start by finding the final velocity of an ion:

$$\begin{aligned}v_f &= \sqrt{\frac{2q(\Delta\phi)}{m}} \\ &= \sqrt{\frac{2(1.602 \times 10^{-19}\,\mathrm{C})(1000\,\mathrm{V})}{(18\,\mathrm{amu})(1.66 \times 10^{-27}\,\mathrm{kg/amu})}} \qquad (3.1) \\ &= 103,600\,\mathrm{m/s}\end{aligned}$$

To obtain the specific impulse, we need to find the thrust of the rocket. Electrically powered rockets are only operated in the vacuum of space. They require strong electric fields that, if used in atmosphere, would break down the air and create an arc that would damage the thruster. Therefore, the ambient pressure around an electrically powered rocket is:

$$p_a = 0\,\mathrm{N/m^2} \qquad (3.2)$$

The mass flow rates of electrically powered rockets are typi-

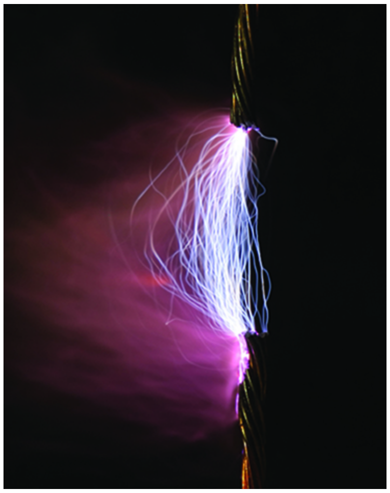

Figure 3: An electrical arc between two metal rods. The arc forms because the electric potential difference between the rods is high enough to generate an electric field that ionizes the air between the rods. Once the air is ionized, current flows along the plasma filament. The plasma quickly heats up and starts to glow.

cally low. We will learn why later on in this lecture. Therefore, we can assume that the exhaust pressure is zero:

$$p_e = 0\,\mathrm{N/m^2} \tag{3.3}$$

As a result, we can ignore the pressure forces acting on an electrically powered rocket. Therefore, the thrust of an electrically powered rocket is:

$$F = \dot{m}c \tag{3.4}$$

Now we can calculate the specific impulse by dividing v_f by g:

$$\begin{aligned} I_{sp} = \frac{F}{\dot{m}g} = \frac{c}{g} = \frac{v_f}{g} \\ = \frac{103,550\,\mathrm{m/s}}{9.81\,\mathrm{m/s^2}} \\ = 10,600\,\mathrm{s} \end{aligned} \tag{3.5}$$

That's 23 times higher than the specific impulse for the best chemical rocket! Electrically powered rockets can easily achieve high specific impulse by using modest voltages. Yes, 1000 volts is considered modest in electric propulsion!

To find the propellant mass fraction, let's apply the Ideal Rocket Equation:

$$\begin{aligned} \frac{m_p}{m_0} &= 1 - \exp\left(-\frac{\Delta v}{gI_{sp}}\right) \\ &= 1 - \exp\left(-\frac{15,000\,\mathrm{m/s}}{(9.81\,\mathrm{m/s^2})(10,600\,\mathrm{s})}\right) \\ &= 0.13 \end{aligned} \tag{3.6}$$

Woah, only 13% of the spacecraft mass needs to be propellant? That means 87% of the spacecraft mass can be payload (and some structure). This is much better!

THE LIMITATIONS OF ELECTRIC PROPULSION

Electric propulsion sounds pretty amazing! But is there a catch?

Power and Efficiency

An important rocket performance metric is the *efficiency* of the rocket engine. This quantity tells us how well the rocket engine utilizes energy to accelerate the exhaust.

DEFINITION 9.1 The **efficiency**, η, of a rocket is defined as the ratio of the *jet power* of the exhaust, $\mathbb{P}_{jet}$, to the total power used to accelerate the exhaust, $\mathbb{P}$.

$$\eta = \frac{\mathbb{P}_{jet}}{\mathbb{P}} \tag{7}$$

DEFINITION 9.2 The **jet power** of the exhaust is the rate of kinetic energy delivered to the exhaust.

$$\mathbb{P}_{jet} = \frac{1}{2}\dot{m}c^2 \tag{8}$$

where $\dot{m}$ is the mass flow rate and c is the exhaust velocity.

Using equations 13 and 14 we can solve for the power used to accelerate the exhaust:

$$\mathbb{P} = \frac{\dot{m}c^2}{2\eta} \tag{9}$$

For an electric thruster, the power used to accelerate the exhaust comes from the electrical power supply. For a chemical rocket engine, the power used to accelerate the exhaust comes from the energy stored in the chemical bonds of the propellant.

Notice that the required power increases with increasing mass flow rate. The more mass you want to accelerate with your thruster, the more electrical power you'll need to operate the thruster. Likewise, the required power increases with the square of the exhaust velocity. As the exhaust velocity increases, and thus the specific impulse, the required power increases quadratically!

Before we discuss the specific limitations of electric thrusters, let's review the types of power sources used on board spacecraft. That way, we'll have an idea of how much electric power is available on a typical spacecraft to power an electric thruster.

Power Sources

1. **Solar Panels** are widely used on satellites and spacecraft. Solar panels work best on spacecraft close to the Sun where the sunlight is strong. As spacecraft travel to the outer reaches of the Solar System, such as to Pluto, the sunlight gets weaker and less power can be extracted using the solar panels. Current solar panel technology can convert 30% of the energy from sunlight into electric power.
2. **Batteries** are often used in tandem with solar panels on Earth-orbiting satellites. The panels are used to charge up the batteries while the satellite is in the sunlight. When the satellite passes into Earth's shadow, it relies on the power stored in its batteries.
3. **Fuel Cells** use chemical reactions to produce electrical power. They are typically used on crewed missions lasting only a few weeks long. They can supply up to 40 kW of power.
4. **Radio Isotope Generators (RTG)** are used to power spacecraft that explore the outer Solar System. RTGs use radioactive material that releases heat as it slowly decays. The heat is converted into electric power using thermocouples. RTGs have flown on exploration missions to the outer Solar System such as Voyager I, Voyager 2, Cassini, and New Horizons.
5. **Nuclear Reactors** have not been used in space before, but they have desirable characteristics. Nuclear reactors produce significant amounts of power, and unlike solar panels, can be used anywhere in the Solar System. However, nuclear reactors have obvious drawbacks including their large size and dangerous radioactive fuel.


Figure 4: Solar panels under preparation for the Juno spacecraft.

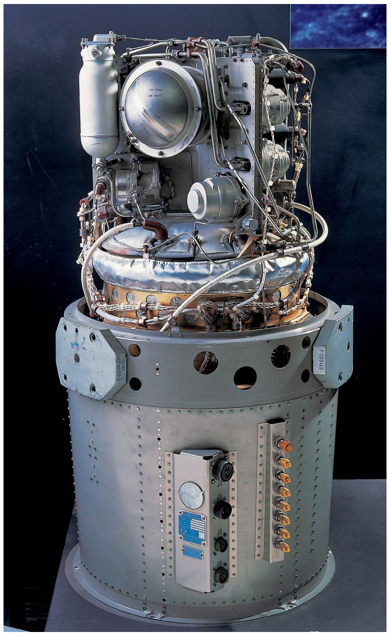
Figure 5: Fuel cell used on the Apollo missions to the Moon.

Thrust Limitation

We can relate the thrust of an electric thruster to the power required to operate the thruster by using the equation: $F = \dot{m}c$. Using this relationship, we can write the equation for required power as:

$$\mathbb{P} = \frac{Fc}{2\eta} \tag{10}$$

Now, let's think about the situation where we want to use an electric thruster for a high delta-v mission. We know we want the specific impulse, and thus exhaust velocity, of the thruster to be high. The electric power on board a typical spacecraft is limited to less than 10 kiloWatts and, perhaps, could supply 1 kiloWatt to a thruster. With limited power and a high exhaust velocity, the thrust and mass flow rate will need to be limited.

Example 4:

Assume the power supplied to an electric thruster is 1 kW. The specific impulse of the thruster is 5,000 s and its power efficiency is 80%. How much thrust can the thruster produce?

First, let's calculate the exhaust velocity using the specific impulse:

$$\begin{aligned} c &= gI_{sp} \\ &= (9.81\,\mathrm{m/s^2})(5000\,\mathrm{s}) \\ &= 490,050\,\mathrm{m/s} \end{aligned} \tag{4.1}$$

Now let's calculate the thrust by rearranging equation 10:

$$\begin{aligned} F &= \frac{2\eta\mathbb{P}}{c} \\ &= \frac{2(0.8)(1000\,\mathrm{W})}{49,050\,\mathrm{s}} \\ &= 0.033\,\mathrm{N} \\ &= 33\,\mathrm{mN} \end{aligned} \tag{4.2}$$

The maximum thrust that this electric thruster can produce without exceeding the limits of its power supply is 33 milliNewtons. For reference, that's approximately the weight of a sheet of paper!

Electric thrusters have high specific impulse, but because of the limited electric power available on a spacecraft, they can only produce very low amounts of thrust. In order to accelerate a spacecraft by a large delta-v, electric thrusters need to be continuously fired for long periods of time to slowly build up the speed of the spacecraft. Sometimes electric thrusters need to fire for months or years to accelerate a spacecraft to the desired final velocity.

Long duration operation of a thruster is called a *non-impulsive maneuver*. Electric thrusters produce low thrust, so these are also called *low-thrust maneuvers*. Non-impulsive maneuvers are the exact opposite of impulsive maneuvers. Remember that chemical rockets are used to perform impulsive maneuvers that involve firing the high-thrust rockets for only a few minutes.

When time isn't critical for a space mission, long duration non-impulsive maneuvers can be used. By using an electric thruster to complete the maneuver, the propellant mass fraction of the spacecraft can be minimized. This means that more payload can be delivered to a particular location, as long as it's acceptable to wait months or years for the spacecraft to arrive.

Let's consider a popular analogy used to illustrate the difference between chemical and electric rockets. Chemical rockets are akin to gas-guzzling sports cars. They go really fast and have a lot of power to accelerate quickly, but they consume significant amounts of fuel. You can't travel far without having to stop and get more gas. They also have small interiors, which means you can't bring very much with you to your destination.

Electric thrusters, on the other hand, are like hybrid SUVs. They're very fuel efficient, so you can drive a long distance before needing to refuel. They also have a large trunk, so you can pack lots of things to bring to your destination. Hybrid SUVs have less power, so they can't accelerate as fast as a sports car. However, over longer periods of time, they can reach their destination with more cargo by using less fuel.

Figure 6: Me waiting for my electric thrusters to bring me to the next star system...

This is a great analogy, but it does have its limitations. The contrast between chemical rockets and electric thrusters is even more extreme than the difference between a Ferrari and a hybrid SUV. If the Ferrari can go from zero to 60 mph in 3 seconds, then the Hybrid SUV would need to take a day to accelerate from zero to 60 mph for this to be a more accurate comparison.

TYPES OF ELECTRIC PROPULSION

There are a wide variety of electric thrusters, which can be grouped into two main categories: electrostatic and electromagnetic.

Electrostatic

Electrostatic thrusters use electric fields to accelerate charged particles. Their design may use magnetic fields, but the magnetic fields are not used for acceleration. There are three main types of electrostatic thrusters:

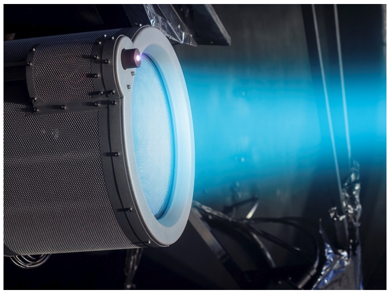

Figure 7: Gridded ion thruster used on the Bepi-Colombo mission to Mercury.

1. **Gridded Ion Thrusters** generate a plasma from a gaseous propellant, usually a noble gas like Xenon or Argon. The plasma is contained in a cylindrical chamber with the exit end covered by a

set of semi-transparent metallic grids. The grids are used to create a strong electric field, which extracts positive ions from the plasma and accelerates them out of the thruster at high velocities. Gridded ion thrusters have high specific impulse and efficiency. This is a mature technology that has been used on a variety of space missions. We'll learn about gridded ion thrusters in Lecture 11!

2. **Hall Thrusters** also generate a plasma from noble gas propellants. The plasma is contained in an annular chamber with the exit end completely open. A moderate electric field is applied to accelerate the ions out of the thruster. Hall thrusters have moderate specific impulse and lower efficiency compared to gridded ion engines. This is also a mature technology that has been used on a variety of space missions.

3. **Electrospray Thrusters** generate charged particle beams from conductive fluids through the application of strong electric fields. The beams consist of ions, charged droplets, or both. Propellants include electrolyte solutions, ionic liquids, and liquid metals. Electrospray thrusters are a type of micropropulsion, which means they produce very low thrust compared to plasma thrusters. This is a developing technology which has flown on a few space missions, including the LISA Pathfinder mission.

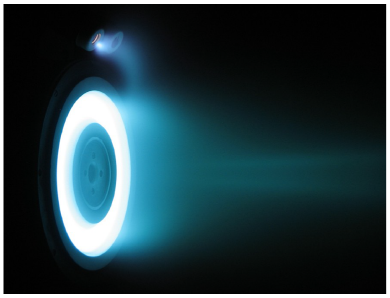

Figure 8: Hall thruster.

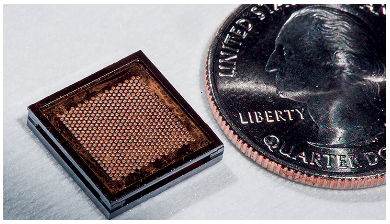

Figure 9: Ion electrospray thruster that uses ionic liquid propellant.

Electromagnetic

Electromagnetic thrusters use both electric and magnetic fields to accelerate charged particles. Some examples of electromagnetic thrusters include pulsed plasma thrusters (PPTs), magnetoplasmadynamic thrusters (MPDs), and the Variable Specific Impulse Magnetoplasmadynamic Rocket (VASIMR). Electromagnetic thrusters produce more thrust than electrostatic thrusters. However, electromagnetic thrusters are less efficient and, therefore, require significantly more electric power to operate. As a result, electromagnetic thrusters have only been used in space a few times.

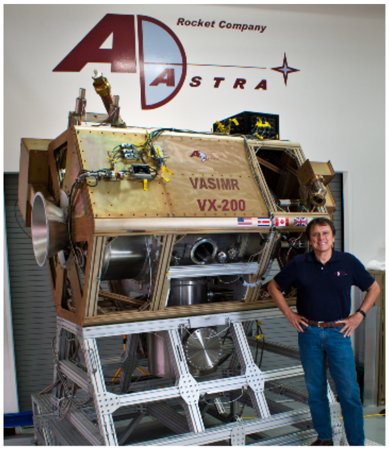

Figure 10: A prototype of the Variable Specific Impulse Magnetoplasmadynamic Rocket (VASIMR).