INTRODUCTION TO ROCKET PROPULSION

L11: Gridded Ion Thrusters

How are plasma thrusters designed?
In this lecture, we're going to build a virtual gridded ion thruster! We'll start by filling a container with our propellant, which is xenon gas. Then we'll learn how to ionize the gas using a cathode, an anode, and magnetic fields. We'll investigate how to accelerate the ions to high velocities and neutralize the exhaust. We'll also estimate the performance and learn why gridded ion thrusters have a maximum thrust density.

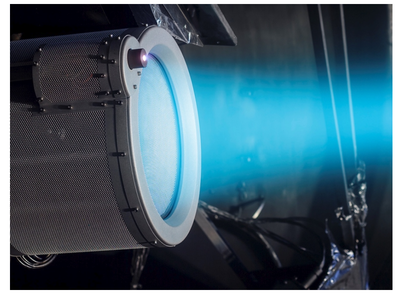

Figure 1: Gridded ion thruster used on the Bepi-Colombo mission to Mercury.

Learning Goals:

1. Describe the three major processes that take place in an operating gridded ion thruster.
2. Explain how a plasma is generated in the ionization chamber.
3. Calculate the final speed of the ions and neutrals in the exhaust of a gridded ion thruster.
4. Quantify the thrust and specific impulse of a gridded ion thruster and explain the assumptions made in the derivation.
5. Explain why gridded ion thrusters are limited to a particular maximum thrust per unit area, or thrust density.

HISTORY OF GRIDDED ION THRUSTERS

The very first plasma thrusters were built during the 1960s. At that time, scientists and engineers realized that high specific impulse rocket propulsion was needed to explore the Solar System. In the early 1960s, NASA scientist Harold Kaufman developed the first gridded ion thruster for practical use. Gridded ion thrusters are often called Kaufman Ion Engines. The Kaufman design is the basis for that of most modern gridded ion thrusters.

Ion thrusters have been used for some really exciting missions! A gridded ion thruster was used on the NASA Dawn mission to the asteroid belt. Ion thrusters were also used on the first "all electric" communications satellite built by Boeing. Most recently, ion thrusters were used on the Hayabusa 2 mission, which returned the first asteroid sample to Earth on December 8, 2020!

Figure 2: The Hayabusa 2 spacecraft with three ion engines operating.

HOW TO BUILD A GRIDDED ION THRUSTER

Gridded ion thrusters ionize a gas and accelerate the positive ions using an electric field. As the name suggests, a set of semi-transparent metallic grids are used to create the electric field that accelerates the ions. In this section, we'll learn how to build a gridded ion thruster! To do so, we'll look closely at the three major processes that take place in gridded ion thrusters:

1. Plasma Generation
2. Ion Acceleration
3. Beam Neutralization

Plasma Generation

The first step is to create a container for the plasma. Gridded ion thrusters are cylindrically shaped. Let's imagine that we have a metallic, cylindrical container like the one shown in Figure 3. We'll call our container the *ionization chamber*. For now, let's assume the two ends (left and right) are closed.

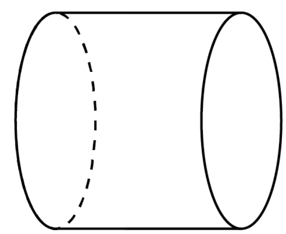

Figure 3: Cylindrical ionization chamber with closed ends. Note: in future diagrams, we'll draw the ion thruster viewed from the side, so the container will look like a rectangle but remember it's a cylinder!

Now, let's make a little hole on the left side of the ionization chamber so we can inject some propellant. In this example we'll use xenon gas. Figure 6 shows the ionization chamber, viewed from the side, filled with neutral xenon atoms.

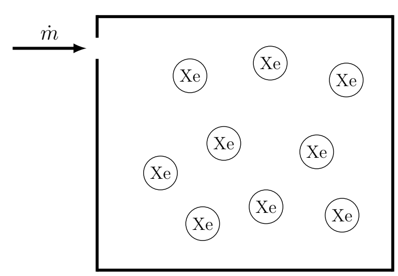

Figure 4: Ionization chamber filled with xenon gas. We don't have a plasma yet!

The next step is to ionize some of the xenon atoms. We can do this using *electron bombardment*. We need to inject some electrons into the ionization chamber, which we can accomplish using a *cathode*.

> DEFINITION 11.1 A **cathode** is an electron source. There are a variety of ways to produce electrons, and, as a result, there are several different types of cathodes used in plasma thrusters. In this course we'll focus on "hot cathodes," which make use of the thermionic emission of electrons from a heated wire.

For our cathode, we'll use thoriated tungsten wire. Thoriated tungsten is mostly tungsten with some thorium atoms mixed inside. The presence of thorium reduces the work function, which is the amount of energy it takes to remove an electron from the metal. We want to choose a material with a low work function because it reduces the amount of energy we need to provide to create electrons.

We can apply a modest voltage across the wire, which will induce a current since the wire has a non-negligible resistance. As current flows through the wire, the metal warms up and starts to glow, just like in an incandescent lightbulb. The cool thing about thoriated tungsten is that when it it's warm, it emits electrons! This is made possible by a process called thermionic emission.

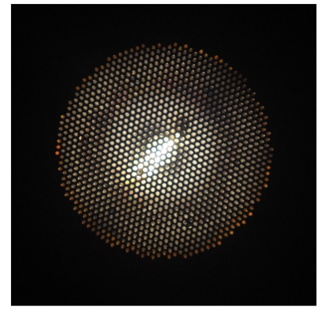

Figure 5: A glowing cathode inside a mini ion thruster without the propellant flowing (there is no plasma in this photo). This photo was taken downstream of the thruster, looking directly into the thruster exit. See Figure 15 for a side view of the operating thruster.

Figure 6 shows the ionization chamber with the cathode installed on the left wall. Now we have electrons in the ionization chamber! However, the free electrons won't ionize the xenon atoms just yet. The electrons have low kinetic energy after being emitted from the cathode, which means they move slowly throughout the chamber. To ionize the xenon atoms, we need faster, more energetic electrons.

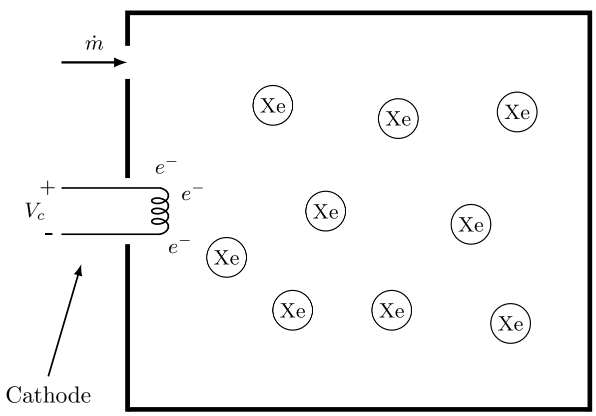

Figure 6: Ionization chamber filled with xenon gas with a hot cathode that emits electrons.

How can we make the electrons go faster? We can apply an electric field and accelerate them. We'll do this by inserting a thin metal cylinder inside the ionization chamber. The cylinder has a diameter that is just slightly smaller than the ionization chamber, as shown in Figure 7. We can positively charge the cylinder, which will attract the electrons leaving the cathode. The charged cylinder is called the *anode* because it collects negative charge. Note that the anode is not in electrical contact with the ionization chamber.

An electric potential, V_A, is used to bias the anode to a positive potential relative to the rest of the ionization chamber. The value of V_A is chosen to be three to four times the first ionization potential of the gas. That way the electrons will have plenty of energy to ionize the neutral atoms once they are accelerated by the anode potential.

Note that we don't want the anode voltage to be too high! In this case, the electrons would have too much energy and might be able to doubly ionize some of the xenon atoms. This would lead to reduced efficiency.

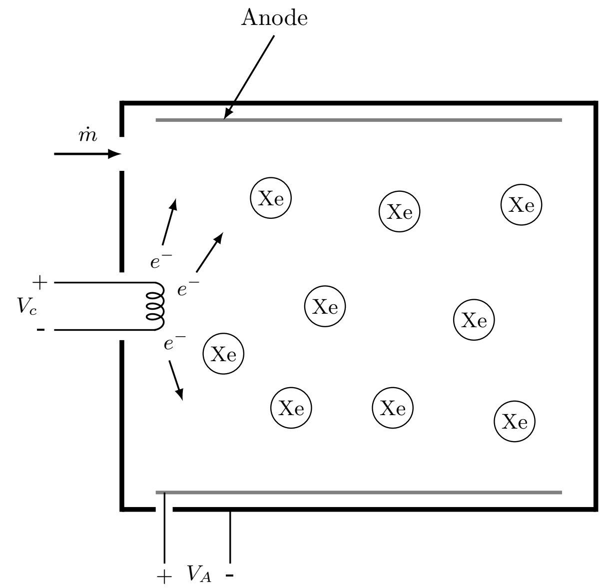

Figure 7: Ionization chamber with an anode installed. The anode is biased to a voltage V_A above the potential of the rest of the chamber. The positive potential attracts and accelerates electrons from the cathode.

Did we make a plasma? Unfortunately, not yet! Even though the electrons have plenty of energy to ionize the xenon atoms, they can only do so if there are collisions. In the configuration shown in Figure 7, the electrons will travel a straight line path towards the anode and arrive there in a split second. The chance of an electron hitting a xenon atom along the way is low! Note: The density of the gas in gridded ion thrusters is low, which makes collisions even less probable.

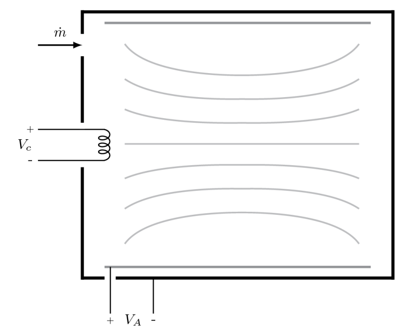

Figure 8: Magnetic field lines generated by an electromagnet. The magnetic field points along the axis of the chamber and is relatively constant in strength.

So what are we supposed to do? We need to keep the high energy electrons in the chamber longer so they have the opportunity to collide with at least one xenon atom. We can accomplish this using magnetic fields. Remember how charged particles can get trapped in a circular orbit around a magnetic field line? If we put a strong enough magnetic field in the chamber, we can trap the electrons so they won't be able to go straight to the anode.

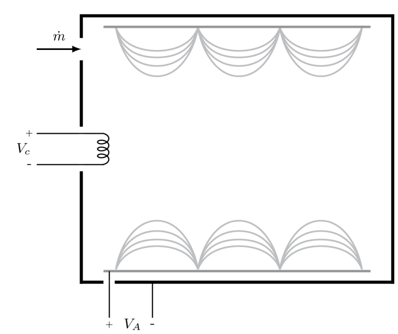

Figure 9: Magnetic field lines generated by permanent magnets surrounding the chamber. These magnetic fields vary in strength along the axis of the chamber. The field strength is highest at the cusps (where the field lines come together) and lowest between the cusps.

There are a variety of potential magnetic field line configurations. Figure 8 shows the field lines created by an electromagnet. In this case, current-carrying wires are wrapped around the outside of the chamber, which generate a magnetic field. Figure 9 shows the field lines created by a set of permanent magnets. The regions of high magnetic field, where the field lines densely cluster together, are called cusps. What's really cool about this configuration is that the electrons trapped on the field lines will bounce back and forth between two cusps. This is called the magnetic mirror effect.

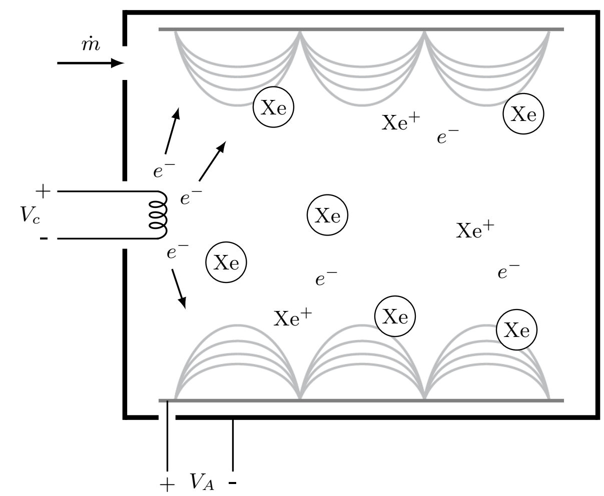

Figure 10: Ionization chamber with a cathode, an anode, and magnetic fields. We finally made a plasma!

Now, after adding the magnetic field, we finally are able to create a plasma! The current configuration of the chamber is shown in Figure 10. Note that the plasma in a gridded ion thruster has a low *ionization fraction*, much lower than what is depicted in Figure 10.

DEFINITION 11.2 The **ionization fraction** is the fraction of the gas that is ionized. It can be computed using the following equation:

$$\alpha = \frac{n_i}{n} \tag{1}$$

where α is the ionization fraction, n_i is the number of ions per unit volume, and n is the number of gas particles (neutral and charged) per unit volume. Note: The number of particles per unit volume is called the *number density*.

Less than 5% of the neutral atoms in a gridded ion thruster are ionized. This doesn't seem like much, but in reality, it provides plenty of ions for acceleration! Later we'll learn that there's a limit to how many ions can be accelerated per unit time, so having more ions in the chamber isn't necessary.

But wait a second, don't the ions get trapped on the field lines too? The Larmour radius is proportional to the mass of the charged particle. As long as the Larmour radius of the ions is larger than the size of the ionization chamber, they won't get trapped on the field lines. The electrons are much less massive than the ions, so they will have a Larmour radius much smaller than the size of the chamber. Ideally, the Larmour radius of electrons should be around a millimeter.

Ion Acceleration

We have a plasma in the ionization chamber, so now it's time to accelerate the ions! Let's start by replacing the right side of the chamber, which is currently a solid piece of metal, with a semi-transparent metallic grid, called the *screen grid*. The potential of the screen grid is the same as the ionization chamber walls. Typically, the screen grid has hundreds, if not thousands, of holes.

Now that the right side of the chamber has holes in it, some of the particles in the ionization chamber can escape! The neutral atoms will pass through the holes as long as their trajectories allow them to do so. They will not experience any forces as they leak out of the chamber, since they are uncharged, so they will exit the thruster at their mean thermal speed, c_n:

$$\bar{c}_n = \sqrt{\frac{8k_B T_n}{\pi m_n}} \tag{2}$$

where k_B is Boltzmann's constant, T_n is the temperature of the neutrals, and m_n is the mass of a neutral atom.

The ions will also readily pass through the holes in the screen grid. However, unlike the neutral particles, the ions are charged and will feel an electric force attracting them towards the grid. Remember that when plasmas come in contact with a metal surface, the surface charges negatively with respect to the rest of the plasma. This means all of the ions will feel an attraction towards the metal surface. In the case of the screen grid, there are lots of holes, so many of the ions will pass right through. As the ions pass through the grid, they do so at a speed called the *Bohm velocity*, denoted by v_B:

$$v_B = \sqrt{\frac{k_B T_e}{m_i}} \tag{3}$$

where T_e is the electron temperature, and m_i is the mass of the ions.

What happens to the electrons? Since the screen grid is negatively charged, the electrons will feel a repulsive force as they approach the grid. Only the most energetic, meaning the fastest, electrons will be able to pass through the grid. This is only a small fraction of the electrons, perhaps less than 5%. Figure 11 shows the ions and neutrals leaving the chamber through the screen grid.

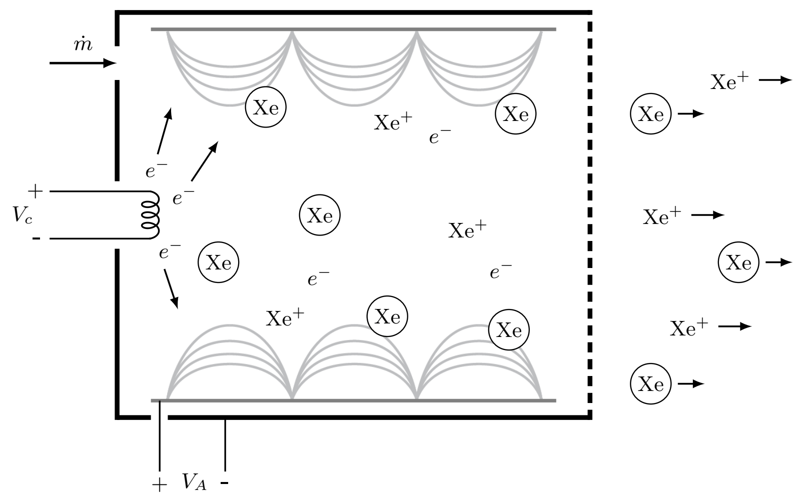

Figure 11: Ionization chamber with a cathode, an anode, magnetic fields, and a screen grid. Here the ions and neutral atoms leave the thruster at low speeds.

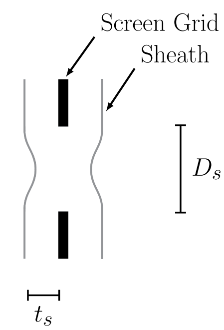

Figure 12: A screen grid hole with diameter D_s viewed from the side. In this case, D_s is smaller than twice the thickness of the plasma sheath, t_s.

We need to be careful about the size of the screen grid holes, because if they are too large, the electrons could leak out. This would be detrimental to the function of the thruster because the electrons are needed to ionize the gas that slowly flows into the chamber. Remember that a sheath layer forms over a metallic surface placed in a plasma. Within the sheath layer, there is an electric field that repels electrons away from the metal surface. Outside of the sheath layer, there is no electric field because the plasma shields the negatively charged surface.

We need to make the screen grid holes smaller than the sheath thickness so that the sheath will completely cover the surface of the screen grid. This design, illustrated in Figure 12, prevents the electrons from escaping. If the holes are larger than the sheath thickness, there will be gaps in the sheath layer where the grid holes are. The electrons can pass through the gaps in the sheath layer since there is no electric field outside of the sheath! This situation is depicted in Figure 13.

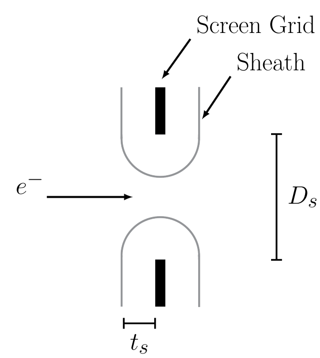

Figure 13: A screen grid hole where D_s is larger than twice the thickness of the plasma sheath. The sheath layer is discontinuous across the screen grid, which allows electrons to leak out!

Assuming the screen grid holes are designed properly, we now have a thruster that exhausts neutral atoms and ions at low speeds, which is depicted in Figure 14. To achieve high specific impulse, we need to make the ions go faster. Let's apply an electric field! We can do this by adding a second grid, called the *acceleration grid*. The acceleration grid is placed just a few millimeters downstream of the screen grid. It has the same number of holes as the screen grid and the geometry is such that the holes of both grids align with each other.

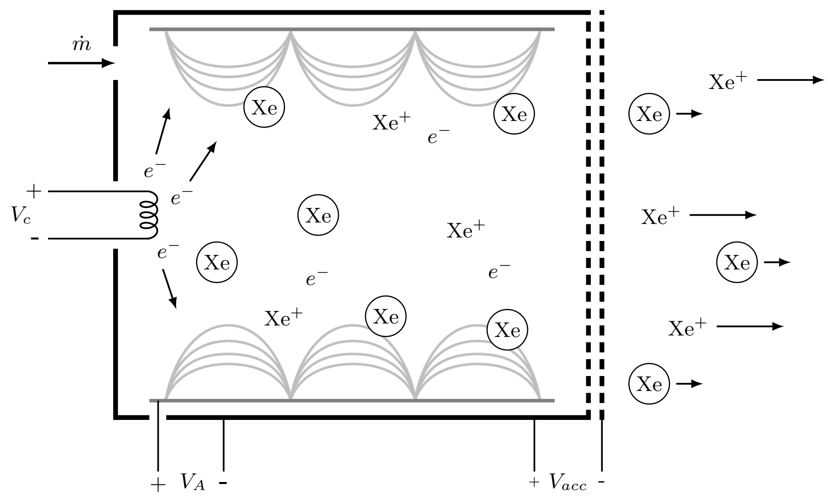

Figure 14: Ionization chamber with a cathode, an anode, magnetic fields, a screen grid, and an acceleration grid. Now we have fast moving ions leaving the thruster!

Assume the acceleration grid is biased to a potential, V_{acc}. What is the final velocity of an ion as it exits the thruster? We can use the conservation of energy, which states that the sum of the ion's kinetic energy and electric potential energy is constant. Let's assume that the ion starts at the screen grid traveling at a speed, v_B, which is the Bohm velocity. The electric potential of the screen grid is, V_s. The conservation of energy can be stated using the following expression:

$$\frac{1}{2}m_i {v_B}^2 + qV_s = \frac{1}{2}m_i {v_f}^2 + qV_{acc} \tag{4}$$

The final velocity of ion is:

$$v_f = v_B + \sqrt{\frac{2qV_{acc}}{m_i}} \tag{5}$$

We successfully accelerated the ions! Are we done designing our ion thruster? Not quite!

Beam Neutralization

The last step in designing an electric thruster is ensuring that the charged particle exhaust is *neutralized*. This means that for every positively charged particle in the exhaust, there needs to be a negatively charged particle. This results in a net zero charge beam. Right now, our ion thruster design only emits positively charged ions and there are no negative charges to balance things out.

What would happen if we didn't neutralize the beam? First of all, the positively charged ions would build up downstream of the thruster. The accumulation of positive charges would create an electric field that would repel ions leaving the thruster. At a certain point, the field would be strong enough to block ions from leaving the thruster, which would effectively stop the thruster from working.

How do we create a neutralized beam? The easiest thing to do is add electrons using a cathode. Typically, a cathode is placed outside of the thruster and is pointed into the beam. The rate of electrons leaving the cathode is set to the rate of positive ions leaving the thruster.

Now we have a working gridded ion thruster! Figure 16 shows a schematic of the final thruster.

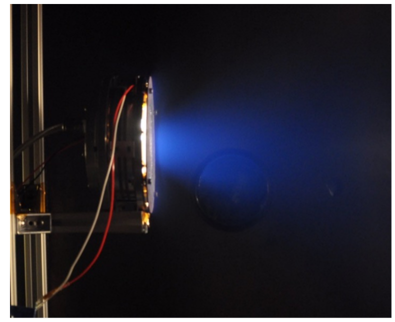

Figure 15: A mini gridded ion thruster! This ion thruster has a diameter of ∼10 cm. It uses argon propellant with a mass flow rate of 5×10^{-8} kg/s.

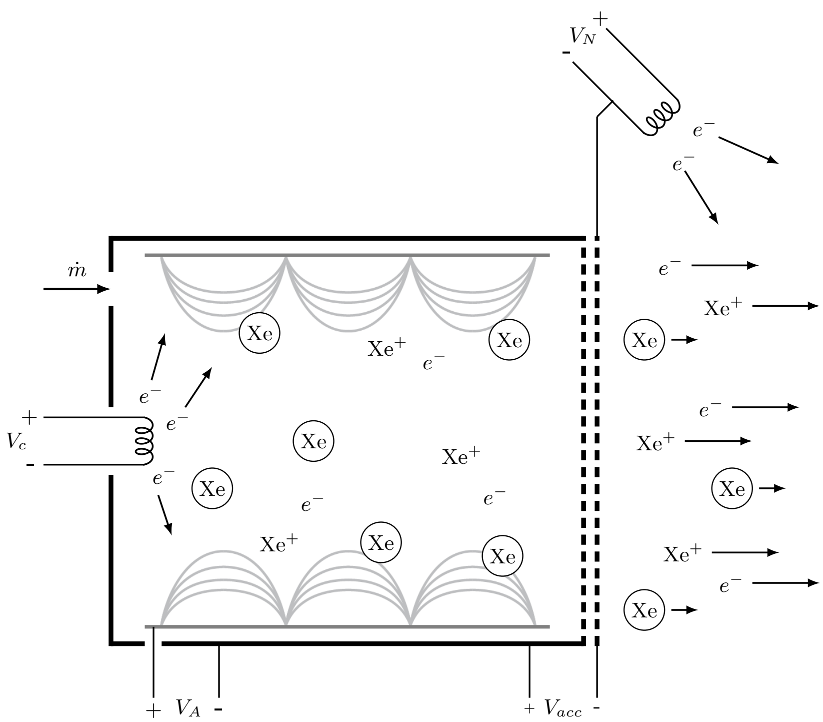

Figure 16: Schematic of a completed gridded ion thruster. The beam is neutralized by the electrons emanating from the external cathode.

GRIDDED ION THRUSTER PERFORMANCE

In this section, we will analyze the performance of gridded ion thrusters. We'll start by estimating the thrust and specific impulse. Then we'll consider any limitations the design imposes on the maximum possible thrust.

Thrust and Specific Impulse

For the majority of electric thrusters, the exhaust pressure is close to zero. Electric thrusters are exclusively operated in the vacuum of space, so the ambient pressure is also zero. Therefore, we do not need to consider the pressure term when estimating the thrust like we needed to with chemical rocket engines. The only term that contributes to the thrust is the momentum flux, $\dot{m}c$.

There are three types of particles in the beam: neutral atoms, positive ions, and electrons. The thrust is the sum of the momentum flux carried by each type of particle in the exhaust:

$$F = \sum_j \dot{m}_j c_j \tag{6}$$

where j denotes a specific type of particle in the beam. For a given type of particle, j, the mass flow rate is $\dot{m}_j$ and the exhaust velocity is c_j. We can write the thrust of a gridded ion thruster as the sum of the thrust from the neutral atoms, positive ions, and electrons:

$$F = \dot{m}_n c_n + \dot{m}_i c_i + \dot{m}_e c_e \tag{7}$$

where the n denotes values for the neutral particles, the i denotes values for the positive ions, and the e denotes values for the electrons. The electrons have a much lower mass than the neutral atoms and positive ions, so we can assume that their contribution to the thrust is negligible. Therefore, the thrust of a gridded ion engine comes from the neutral atoms and ions only:

$$F = \dot{m}_n c_n + \dot{m}_i c_i \tag{8}$$

We know how to calculate the exhaust velocities of the neutral atoms and positive ions. What about their mass flow rates? By the conservation of mass, we can say that the sum of the mass flow rates of neutral atoms and positive ions leaving the thruster must be equal to the total mass flow rate of propellant into the thruster:

$$\dot{m} = \dot{m}_i + \dot{m}_n \tag{9}$$

When analyzing ion thrusters, a quantity called the *utilization efficiency*, η_u, is used:

$$\eta_u = \frac{\dot{m}_i}{\dot{m}} \tag{10}$$

The utilization efficiency of a typical gridded ion thruster is 80%.

Now we can write the thrust in terms of the mass flow rate and the utilization efficiency:

$$F = \dot{m}\Big((1-\eta_u)c_n + \eta_u c_i\Big) \tag{11}$$

Finally, we can estimate the specific impulse of a gridded ion thruster:

$$\begin{aligned} I_{sp} = \frac{F}{\dot{m}g} &= \frac{\dot{m}\Big((1-\eta_u)c_n + \eta_u c_i\Big)}{\dot{m}g} \\ &= \frac{1}{g}\Big((1-\eta_u)c_n + \eta_u c_i\Big) \end{aligned} \tag{12}$$

The contribution to the specific impulse by the neutral atoms is very small, because they exit the thruster at low speeds. Therefore, we can approximate the specific impulse using the following equation:

$$I_{sp} = \frac{\eta_u c_i}{g} \tag{13}$$

Example 1:

Let's estimate the specific impulse of a gridded ion thruster that uses xenon gas. We'll assume that the potential difference between the grids is 1.5 kilovolts and that the utilization efficiency is $\eta = 0.8$. We'll also assume that only singly charged ions are produced and that the electron temperature is 20,000 K.

The Bohm velocity of the ions falling into the acceleration region is:

$$\begin{aligned} v_B &= \sqrt{\frac{k_B T_e}{m_i}} \\ &= \sqrt{\frac{(1.38 \times 10^{-23}\ \mathrm{kg \cdot m^2/s^2 \cdot K})(20,000\ \mathrm{K})}{(131\ \mathrm{amu})(1.66 \times 10^{-27}\ \mathrm{kg/amu})}} \\ &= 1,127\ \mathrm{m/s} \end{aligned} \tag{1.1}$$

The velocity of the ions leaving the thruster is:

$$\begin{aligned} v_f &= v_B + \sqrt{\frac{2q(V_s - V_{acc})}{m_i}} \\ &= 1,127\,\text{m/s} + \sqrt{\frac{2(1.602\times10^{-19}\,\text{C})(1,500\,\text{V})}{(131\,\text{amu})(1.66\times10^{-27}\,\text{kg/amu})}} \\ &= 48,138\,\text{m/s} \end{aligned} \tag{1.2}$$

Finally, the specific impulse of the thruster is:

$$\begin{aligned} I_{sp} = \frac{\eta_u c_i}{g} &= \frac{(0.8)(48,138\,\text{m/s})}{9.81\,\text{m/s}^2} \\ &= 3,926\,\text{s} \end{aligned} \tag{1.3}$$

Thrust Limitation

Is there a maximum thrust that a gridded ion thruster can produce? With chemical rockets, we can increase the mass flow rate indefinitely to achieve high thrust. At some point there is a limit because it is perhaps impractical or impossible to supply such high mass flow rates with today's technology. However, there is no theoretically imposed limit to the thrust a chemical rocket can produce.

Gridded ion thrusters are of course limited by the amount of electrical power available, like all electric thrusters. However, this is a limitation imposed by available technologies. One day, it might become much easier to produce enormous amounts of electrical power on board spacecraft. But is there a theoretical limit to the thrust of a gridded ion engine? Can we increase the mass flow rate indefinitely?

In short, the answer is no. There is a theoretical maximum thrust per unit area that ion engines can produce. This happens because there is a maximum possible current, or ions per unit time, that can be accelerated through the grids. The region between the grids, which we will call the *acceleration region*, is a non-neutral region. The only charged particles that enter this region are the positive ions. As we increase the mass flow rate of the thruster, the number of ions in the acceleration region will increase.

Just like in the scenario of an un-neutralized beam, the ions can build up between the grids and start to repel new ions from entering the acceleration region. At some point the ion density in the acceleration region will reach a critical limit in which the electric field from the ions cancels out the accelerating electric field. The ions entering the screen grid will no longer feel an electric field to pull them into the acceleration region. When this happens, the maximum mass flow rate of ions that the grids can accelerate has been reached.

The gridded ion thruster is called a *space charged limited* device. There is a limit to the rate at which ions can be accelerated out of the thruster, due to the *space charge* between the grids. Since the mass flow rate of a gridded ion thruster has a maximum value, then there is a maximum possible value of the thrust. More specifically, the mass flow rate per unit area and thrust per unit area, called the thrust density, are limited. We can express the maximum thrust density of an ion thruster using the following expression:

$$\left.\frac{F}{A}\right|_{max} = \frac{8}{9}\epsilon_0\left(\frac{\Delta V}{d}\right)^2 \tag{14}$$

where A is the area of the thruster exit, ΔV is the potential difference between the screen grid and the acceleration grid, and d is the separation distance between the two grids.

Notice that the maximum thrust density increases with increasing potential difference. This makes sense because a higher potential difference means that ions are moved through the acceleration region faster, which gives them less of an opportunity to build up. The maximum thrust density decreases with increasing grid spacing distance because the larger the distance, the weaker the accelerating electric field. It takes less ions to cancel out a weaker field than a stronger field.

Example 2:

Let's estimate the maximum thrust density of a gridded ion thruster. Typically, the potential difference between the grids is 1.5 kilovolts and the spacing between the grids is 3 mm. Let's apply equation 14:

$$\begin{aligned}\left.\frac{F}{A}\right|_{max} &= \frac{8}{9}\epsilon_0\left(\frac{\Delta V}{d}\right)^2 \\ &= \frac{8}{9}(8.854\times10^{-12}\,\mathrm{Nm^2/C^2}))\left(\frac{1500\,\mathrm{V}}{0.003\,\mathrm{m}}\right)^2 \\ &= 2\,\mathrm{N/m^2}\end{aligned} \tag{2.1}$$

Figure 17: We made it to the end of the course! :D