An Introduction to Ion Thrusters

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Presented to:
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May 3, 2015

Abstract

We explore the mechanism used to generate thrust in the ion propulsion systems that are in common use on spacecraft. We also discuss some potential methods of further acceleration of the ions by means inspired by particle accelerators, and explore the practicality of their implementation in ion thrusters. In this we find that, at this time, these methods don't seem to offer much in the way of increased effectiveness for ion thrusters, but may at some point, pending the discovery or invention of strong power sources with very low mass.

1 Introduction

In March of 2015 NASA's Dawn space probe settled into orbit around its final destination after a long trek across the solar system. In doing so, it became the first spacecraft to orbit two extraterrestrial objects (an earlier stop being Vesta – another dwarf planet) [1]. Just over one tenth of Dawn's 1240 kg (wet) mass is contained in its ion propulsion system [2]. This propulsion system, using a 450 kg tank of xenon gas, along with a gravitational assist by Mars, allowed the spacecraft to orbit multiple targets, where the use of chemical propulsion in the past has only allowed spacecrafts to study multiple targets during flybys, due to the much larger fuel consumption [3]. The efficiency of the xenon ion propulsion system coupled with long periods of time for acceleration allowed for the probe to achieve a ΔV of 11 km/s despite the very small thrust provided ($< 92mN$) [2].

In light of these impressive statistics for just one of many missions using a xenon ion thruster, it is not hard to imagine why the number of missions employing them as their propulsion system has been increasing ever since the first successful implementation (Deep Space 1, launched in 1998) [1], nor why they have become a favorite among science fiction writers.

The basic idea is simple conservation of momentum. If something is thrown out of the back of a vessel with some momentum $\vec{P}$, the vessel will gain the same momentum in the opposite direction by gaining forward velocity. This is the same principle as in any rocket. Chemical propulsion, however, relies on the rapid expansion of gas to provide the velocity of the ejected material and ion propulsion uses electrical energy (usually from solar panels or a reactor) to accelerate ions to much higher velocities as they are ejected. This allows for each individual particle to provide a higher impulse on the craft than in chemical propulsion, allowing for the use of less fuel to reach similar velocities.

The physics used in actually accomplishing this form of propulsion in ion thrusters will be discussed in section 2, being broken down into discussions of the mechanisms employed in the creation of the ions (section 2.1) and acceleration of these particles before they are ejected (section 2.2). We will then, in section 3, compare the methods used in ion thrusters to other means of accelerating ions and explore the potential for each to increase the thrust. In section 4 we will recap and compare the different methods of propulsion discussed in the previous sections, hazarding some comments on their potential impact on the effectiveness of ion thruster technology.

2 Generating Thrust

There are many different proposed setups for the organization, shape, and power needs for ion propulsion systems [2, 3, 4, 5, 6]. They all, however, share two main things. They must have a source of ions or create them, and they must accelerate said ions before or during expulsion.

Most of the proposed and existing thrusters (including those on Dawn) create the ions in the same chamber as the acceleration, and the ions are being accelerated even while they are being stripped of electrons [2, 3, 4]. In some setups, however, (such as the Dual Stage 4 Grid ion thruster) the ions are created in one chamber, then are moved to another for acceleration [5]. A few proposed designs even rely on ionic liquid as their ion sources, doing away with the need for an ionization stage altogether [6], though we will focus here on the thrusters that require the creation of ions. Regardless of the location and timing of the ion generation with respect to the acceleration, they are still two separate processes and we shall explore them individually.

2.1 Creation of Ions

To accelerate ions in an attempt to generate thrust, one first needs ions. In most incarnations of the ion thruster, a propellant gas is stored in a tank in liquid form, then as it enters the thruster, it is ionized. The propellant usually chosen is xenon [3]. In theory, one could potentially use any gas, as long as they develop an efficient method for ionization. Xenon, however, is a good choice for several reasons. Being a noble gas, xenon is generally nonreactive and, thus, minimizes corrosion. A large amount of the energy consumed by the drive goes into the ionization process, so choosing a propellant with a low ionization energy would decrease power consumption. Xenon, having the lowest ionization energy of nonradioactive noble gases (3.893 eV [7]), provides this low ionization energy while still being both safe and noncorrosive.

For ionization, the xenon atoms are usually bombarded with high energy electrons [3] or electromagnetic fields. Magnets are used to attract both the shed and ionizing electrons (if used) and collect them. The collected electrons are generally emitted out the back of the thruster along with the positive stream of propellant to avoid a build up of negative charge in the ship, which would attract the ejected ions back to it, rendering this method of propulsion about as effective as filling one's sails using a deck-mounted fan.

In Hall thrusters the ionization mechanism is very similar. However, instead of launching high energy electrons into the gas the ionizing electrons are emitted from the rear of the thruster and a strong electric field is used to pull them into the thruster where they encounter a radial magnetic field coming from a cylinder centered in the cavity (parallel to the direction of desired thrust). Having a velocity towards the upsteam end of the thruster while traveling through this magnetic field causes it to spin around the central cylinder (this is called a Hall current). Xenon particles injected into this electron gas are ionized by collisions.

2.2 Acceleration of Ions

When a current exists and a magnetic field is applied to it, a potential difference appears perpendicular to both the current and the magnetic field. This is called the Hall effect [7]. In the Hall thrusters previously discussed, the electrons orbiting the central cylinder provide a current and their interaction with the radial magnetic field, by way of the Hall effect, creates a potential difference. The direction perpendicular to both the current and magnetic field is in the direction of desired thrust. The newly ionized xenon particles are both repelled by the anode at the front of the thruster and accelerated by this potential difference and are ejected out the back of the thruster, providing a forward impulse to the ship. Another way to say this is that the acceleration is caused by the Lorentz force

$$\vec{F} = q[\vec{E} + \vec{v} \times \vec{B}], \tag{1}$$

but there is a certain amount of satisfaction to be gained by describing the thrusters using the phenomenon from which it takes its name. In this case, because there are already electrons flowing out the back of the ship, among the flow of ions, some will be attracted to the ions and be carried off with the stream, avoiding the build up of negative charge previously discussed.

Another method of accelerating the ions is by the use of charged grids, the plane of which is perpendicular to the desired direction of thrust. This creates an electric field in that direction between the grids. This is called a gridded ion thruster for obvious reasons [8]. The positive grid is placed upstream and the negative grid is placed downstream (because the ions carry a positive charge; this would be reversed if one were to use anions). Once an ion enters this field, the Lorentz force (which is the same as the Coulomb force in the absence of a magnetic field) accelerates the positively charged particle out the back of the thruster. The velocities involved are small (20-50 km/s [3]), relativistically speaking (notice that $50km/s = \frac{5}{3} \times 10^{-4}c$):

$$\gamma = (1-(v/c)^2)^{-\frac{1}{2}} < \left(1 - \left(\frac{5}{3} \times 10^{-4}\right)^2\right)^{-\frac{1}{2}} \approx 1 + \frac{1}{2}\frac{25}{9} \times 10^{-8} = 1.000000014 \approx 1. \tag{2}$$

So, to determine the resulting acceleration one only need consider Coulomb's law and Newton's second law.

How, though, does a positively charged ion end up between the two grids, if the upstream grid is the positive one? This is achieved, simply, through thermal pressure. As more atoms get pushed into the ionization area and get ionized, the pressure of the ion gas pushing toward the grid increases. Since it is a grid, not a solid sheet of charge, there are gaps in it that are large compared to the size of the ions. When a positive ion is pushed close to the grid there are, potentially, positive charges in any direction exerting a repulsive force, aside from the direction of the gap (while there doesn't necessarily have to be an ion in any specific location behind it, the point is that there CAN be an ion in any direction aside from the gap). Statistically, then, the thermal jostling of the ions is likely to push the ion through the gap, into the space between the grids, where, as we have already discussed, it accelerates away.

3 Comparison to Particle Accelerators

A reasonable response to the realization that ion thrusters aren't accelerating particles to relativistic speeds, especially by those familiar with the incredible speeds reached by particles at particle accelerator or collider facilities, might be to wonder why the exhaust speed is so low. After all, if the exhaust speed were to double, so too would the impulse, and who hasn't seen references to the amazingly high speeds with which particles are moving at the Large Hadron Collider or the Stanford Linear Accelerator?

If, for the sake of comparison, we were to determine the impulse imparted by a single xenon ion accelerated to 50 km/s, where atomic xenon has a mass of 131.29 u ($1.2231 \times 10^5 MeV/c^2$) and we assume that this is the mass of the ion, because it is close enough, we would find

$$P = \gamma mv \approx mv = (1.2231 \times 10^5)\left(\frac{5}{3} \times 10^{-4}\right) = 20.385\frac{MeV}{c} = 1.0886 \times 10^{-20}\ \frac{kg\ m}{s} \qquad (3)$$

where we relied on equation 2 to show that, in this case $\gamma \approx 1$. So, if we have a 1000 kg ship (just lighter than Dawn), a mol of xenon would cause an increase in velocity of roughly 6 $\frac{m}{s}$. For comparison to other methods in future arguments, we may also benefit from determining the kinetic energy of the particle

$$T = \frac{1}{2}mv^2 = \frac{1}{2}(1.2231 \times 10^5)\left(\frac{5}{3} \times 10^{-4}\right)^2 = .0016988\ MeV = 1.6988\ keV \qquad (4)$$

where we have, again, assumed that the speeds involved are too small for relativistic effects to matter.

A particle accelerator starts off, essentially, in the same way that an ion thruster does. There is an ion source, then the ion is accelerated away from the source by means of an electric field to enter the rest of the accelerator, using a magnetic field to focus the beam. The difference is that instead of that being the end, as in an ion thruster, the beam is then accelerated again and again by more and more exposure to electric fields, and refocused (and steered, if necessary) by magnetic fields provided by quadrapole (and dipole) magnets.
There are 3 main types of particle accelerators [9] that each have their own methods of acceleration, and we will explore each in turn.

3.1 Electrostatic Accelerators

Electrostatic accelerators use a static electric field to accelerate the particles, in precisely the manner already discussed because, in fact, gridded ion thrusters are low energy electrostatic accelerators. The addition of larger potentials on the grids would increase their thrust. This is a method that is already being explored [5], and inhibited mostly by the limited source of power available (something that the reader may find as a reoccurring theme, as they read onward). There is also an upper limit on this technology for the energies of outgoing particles of about 10 MeV due to an upper limit of roughly 10^7 Volts [9] as a potential difference between the two electrodes.

3.2 Cyclotrons

Cyclotrons use a large, uniform magnetic fields perpendicular to the direction of movement such that, in the absence of any electric field, the ions would travel in a circle. The circular path is then incased in two half disks (called “dees”) that have opposite potentials and are separated by a small gap. Every time an ion leaves the higher potential dee for the lower, the ion is accelerated. By creatively timing the switching of these potentials, one can assure that the ions are being accelerated every time they hit the gap. As they speed up, the ions orbit at a larger and larger radius, slowly spiraling outward to where they can be emitted. This setup, in the idealized case, would lead to a maximum ion exhaust velocity of [9]

$$v_{max} = \frac{qBR}{m} \tag{5}$$

where q and m are the ion’s charge and mass, respectively, and B and R are the constant magnetic field applied to the ion beams and the maximum radius at which the field is applied. At first glance, this looks like there should be no limit to the maximum velocity, as one could keep making B larger or increasing the radius, or both. However, there are several limiting factors. The first is that for particles with over about 40 MeV relativity becomes important [9]. In fact, to particles with such high velocities the magnetic field is distorted. The answer to this upper energy limit due to relativistic effects is the synchrocyclotron, where the frequency is varied as the particles make their way further and further from the center. Unfortunately, this renders the smaller radii useless, meaning that accelerated ions can only come in bunches, rather than a continuous stream [9]. Ignoring the issues of the increase in mass due to added equipment, this need to operate in pulses drastically decreases the flux of particles being tossed out the back of the ship. So, even though the particles could have a higher energy, the fact that there are fewer of them would decrease the overall thrust. The 40 MeV limit noted above is still a sizable improvement over the maximum energy determined for our thruster in equation 4. In fact, it is an improvement by a factor of roughly twenty-three thousand. Upper limit or not, this increase warrants exploration. It is important to remember now that the thrust isn’t all that matters in the acceleration of the spacecraft. We must consider mass as well, and that, as we will see, will be what strikes this potential source of acceleration its killing blow. First, launching heavy objects into space is incredibly expensive. So, even if we were to determine a scheme where a very heavy thruster supplied adequate thrust to accelerate a ship to high velocities, getting it into space would be very expensive. Assuming, though, that we have a limitless budget, is there anything else to stop us from using a large cyclotron thruster? It turns out that inertia is going to cause problems.

As any introductory physics text will show [7], the velocity gained by an impulse applied to an object is inversely proportional to its mass. That is to say, if we effectively double the impulse delivered by an ion, but double the mass of the thruster in the process, we gain nothing in terms of actual acceleration or top speed. Assuming we use Helmholtz coils to produce our uniform magnetic field, a bare minimum of material for a cyclotron (ignoring all the masses of casing material) then we can approximate the mass to be

$$M_{total} = 2M_{dee} + 2M_{coil} + C \tag{6}$$

where C is some constant amount of mass for electronics and the ion source, M_{dee} is the mass of each dee (of which there are 2), and M_{coil} is the mass of each coil (of which there must also be 2). For the sake of argument, we will restrict the mass of each coil to just the mass of copper wire (with a radius r) used to wrap the coil, and the mass of each dee will only be the mass of material in the walls of a thin, short half cylinder with a height h and a wall thickness w (notice that this will result in a vast underestimation of the mass). It's not hard to see that

$$M_{dee} = \frac{1}{2}(2w(\pi R^2) + h \cdot w(2\pi R)) \cdot \rho_{dee} = \pi w \rho_{dee} R(R + h) \tag{7}$$

$$M_{coil} = (n2\pi R)(\pi r^2)\rho_{Cu} \tag{8}$$

$$M_{total} = 2(\pi w \rho_{dee} R(R + h)) + 2((\pi r^2)(2\pi R)\rho_{Cu}) = 2\pi R(w\rho_{dee}(R + h) + 4n\pi r^2 \rho_{Cu}) + C \tag{9}$$

where ρ_{dee} and ρ_{Cu} are the densities of the material used to make the dees and copper, respectively, and n is the number of times the coil is wrapped. To determine the change in speed of the ship due to the exhaust of an ion

$$\Delta v_{ship} = \frac{p_{exhaust}}{M_{ship}} = \frac{m \cdot v_{max}}{M_{total}} = \frac{qBR}{M_{total}} \tag{10}$$

In the case of a Helmholtz coil being the source of our magnetic field,

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 n I}{R} \tag{11}$$

where I is the current running through the wire. In fact, Helmholtz coils are not likely to be the source of the large magnetic field necessary for use in a cylcotron, however, since a Helmholtz coil is just a ring of wire (the interior being empty) it is not a bad place to start, for its low mass. Combining equations 10, 11, and 9 we get

$$\Delta v_{ship} = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 n I}{R} \cdot \frac{qR}{M_{total}} = k_v \frac{qnI}{R(w\rho_{dee}(R + h) + 4n\pi r^2 \rho_{Cu}) + C} \tag{12}$$

where we let k_v be the constant $\left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0}{2\pi}$ in an attempt to declutter the math. There are a few things worth noticing about equation 12. First, both the numerator and denominator are linear with respect to n, so just adding more wraps to the coil won't actually increase the speed boost. Secondly, any increase in R (the radius of the cyclotron) decreases the gain in velocity of the ship, because the mass (which, recall we grossly underestimated) increases faster than the increase in thrust. The only way for this system to actually give the ship any decent amount of increase in velocity, then, would be to increase q or I without substantially increasing the mass overhead, C.

So far, this discussion has completely avoided the issue of the enormous power requirements for a cyclotron. In fact even a modest increase in the electrical current, I, will increase the mass of the power system (which would be a large part of mass C), at our current level of technology. If one were to devise a very light means of generating an enormous current, however, it is not an unreasonable means of further accelerating the ions and increasing the thrust.

3.3 Synchrotrons and Linacs

A Linac (short for "linear accelerator") is an accelerator that, as the name suggests, accelerates the particles in a straight line. The method of acceleration can either be that of electrostatics (discussed in section 3.1), or by rapid switching of charged tubes. In this second setup, at any given instant the system looks like a series of electrostatic accelerators, the particle just expected to travel in the direction of decreasing potential. The charge, however, is actually governed by use of radio waves slowed as they travel through an RF cavity (RF standing for "radio frequency"), thus the charge on the tubes increase and decrease periodically. When timed correctly, this allows a positive ion to always have the tube behind it to have a positive charge (pushing it forward) and the tube in front of it to have a negative charge (pulling it forward). As the particle begins to move faster, either the length of the tubes or the driving frequency need to change, otherwise the particle will no longer find itself always rolling downhill, so to speak.

A synchrotron is, more or less, a Linac as discussed above, but it also uses dipole magnets to curve the beam around in a circle, thus allowing the same section of tube to be used repeatedly. In both of these cases, continuous beams are turned into discrete groups of particles due to phase stability [9]. A series of pulses can still result in a very high current and, thus, be used to create a good deal of thrust. However, while a linac can handle an ongoing series of pulses and will, thus, be discussed further, the reuse of real estate that makes synchrotrons like the Large Hadron Collider so powerful for high energy collisions causes its downfall with respect to consideration for ion thrusters, as it does away with this ability.

In theory, a Linac would work wonderfully for a thruster, as radio waves have no mass, and this method can be used to accelerate particles to incredibly high energies. For example, electrons in the Stanford Linear Accelerator get up to energies in the range of 50 GeV [9], which is a factor of $\sim 10^4$ times larger than the current ion thrusters. Unfortunately, once again, the issue here is the mass. While the thrust achievable may be 10,000 times greater, the Stanford Linear Accelerator is a building that is almost 2 miles long (making it the longest building in the United States) which, one can bet, is more than 10,000 times more massive than the Dawn space probe (unfortunately, the actual masses of such installations isn't a readily available piece of information, because the prospect of launching it into space, apparently, isn't often considered). Why, though, not just use the method on a smaller scale to increase the thrust? After all, terrestrial particle accelerators are not really built with the minimization of mass in mind, and a lot of mass should, in principle, come from the fact that the beam must be kept in a vacuum – something that we get for free in space.

To ensure any amount of efficiency, a RF cavity should be fed a very specific wavelength of radio waves; all other radio waves will be wasted energy and will hurt the efforts to synchronize.

Also, for the particles to be accelerated much at all, the power output in the form of radio waves needs to be huge, so as to create decently sized electric fields. The commonly used radio source for Linacs is a klystron (SLAC, mentioned above, has over 200 of them along the tube). A quick look at Toshiba's web page about the klystrons they make, will show that efficiencies over 60% are rare, and the power requirements are huge. While some of the units themselves aren't actually that massive (with a range of masses between 5 and 1300 kg, the general trend being that of more mass for more output power), many of the lighter units require a water cooling system, which will greatly increase the mass when in use. The large power requirements return us to the dilemma discussed at the end of section 3.2 with respect to the fact that power systems are very heavy.

4 Conclusions

We have discussed the general types of ion thrusters in use and how the technology used in particle accelerators might help to increase the acceleration by ion thrusters by helping to increase the ion exhaust speed. It was determined that, while many methods are unreasonable for implementation in an ion drive, a cyclotron could, potentially be used, if an incredibly light source of very high electrical current were to be used to power it, and a very light conducting material were used for construction of the dees. We also found that RF cavities might be used to increase the velocities, but again, would rely of very strong power sources with next to no mass. As things sit right now, technologically speaking, ion thrusters don't stand to gain much in the way of effectiveness by the application of acceleration methods stolen from particle accelerators. As a means of propulsion, though, they have great potential.

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