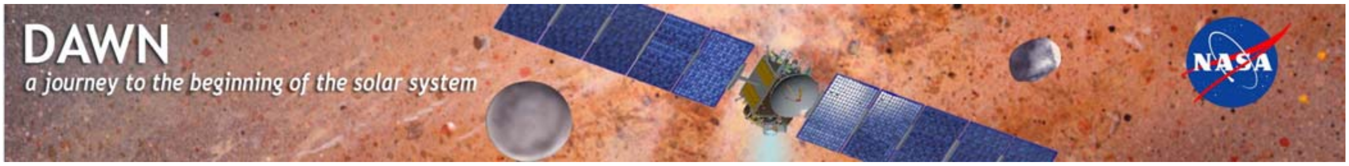


Ion Propulsion

A Trip through an Ion Propulsion Engine

STUDENT READING

The most significant descriptor of this graphic is “simplified.” If you have read the student texts entitled “Pushing with Plasma” and “Charges,” you realize that what is happening in the mixture of gaseous particles in an ion engine chamber is very complex. However, in this graphic, we will focus on what a xenon atom (or ion) “sees” and “does” as it goes through the reactions and processes that provide the ion jet propulsion engine’s thrust.

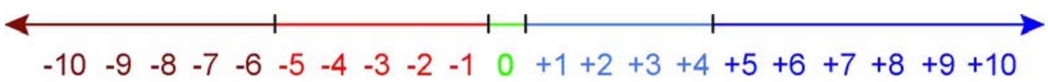
The color scheme in these graphics is the same as that used in the tutorials for the Student Activity “Positive and Negative Charges” simulation. Negatively-charged electrons are red, positively-charged ions are blue, and neutral atoms are green.

You can think of the **relative charges** on the grids, the chamber, the electrons, and the xenon ions as being similar to that of signed numbers on a number line.

Relative Charge Number Line

Negative charge strengths

Positive charge strengths



In the tutorials, you assigned charge strengths to the particles that you placed in the chamber. When you changed the strength on a negative particle from 5 to 10, the size of the particle increased. This also means that you moved to the left on the charge number line. In other words, a particle with a –5 charge is more negative than the positively-charged test bullet, but it is also less negative than the particle with –10 charge.

When you change the strength of a positively-charged particle from 5 to 10, you move to the right on the number line. So, the particle with +5 charge is less positive than the particle with +10 charge, but more positive than any particle that is to the left of it on the number line. As we trace the path of a xenon ion through an ion engine, we must think in terms of relative positive and negative charges.

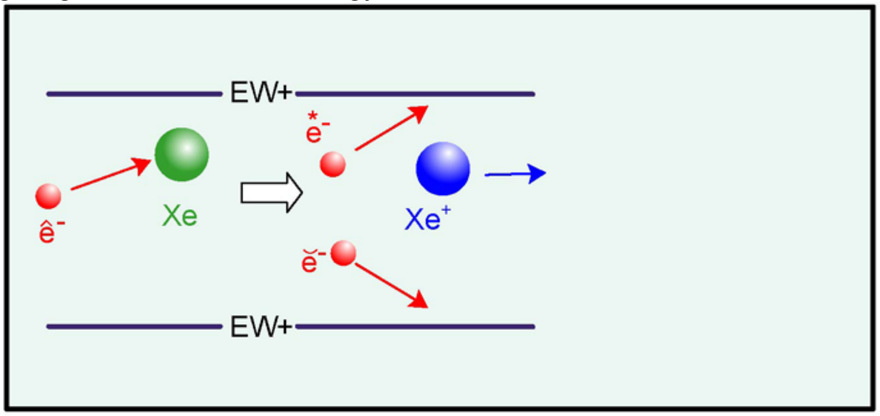
As the xenon plasma moves through the ion engine, the charges on the parts of the engine that it encounters are in the **reverse order** of the signed number line; that is, in order of increasing negative charge.

engine walls < xenon ion plasma < first electrode grid < second electrode grid

It is important to remember that some processes in the ion engine depend upon the ***difference in magnitude*** of the charges on particles, the chamber, and grids.

1. Ionization process

When a solar-powered ion engine is running, energetic electrons are emitted from a hollow-tube cathode. These electrons enter the ionization chamber where the positive engine wall attracts them, giving them additional energy to ionize the xenon atoms.



In this graphic, ê⁻, represents an electron with sufficient energy to ionize a xenon atom. As it travels toward the engine walls, it undergoes an *inelastic* collision with a xenon atom Xe, to form a xenon ion Xe^+ and another electron, ĕ⁻. e*⁻ is the electron that was involved in the collision, but it is now at a lower kinetic energy than it had prior to the collision. The electrons present after the collision are attracted to the engine walls.

The "Pushing with Plasma" student text describes the many types of collisions that charged particles can undergo while in a mixture of atoms, ions, and electrons. However, if the xenon ion Xe^+ is to contribute to the thrust of the ion engine, it *must* remain a charged particle and instead of moving randomly in the chamber, it must also be aligned to move in the same direction as other xenon ions toward the rear of the engine.

Why Xenon?

Xenon is a desirable propellant gas for ion propulsion for three reasons. First, it is an inert gas, so corrosion reactions with the metal chamber are minimal.

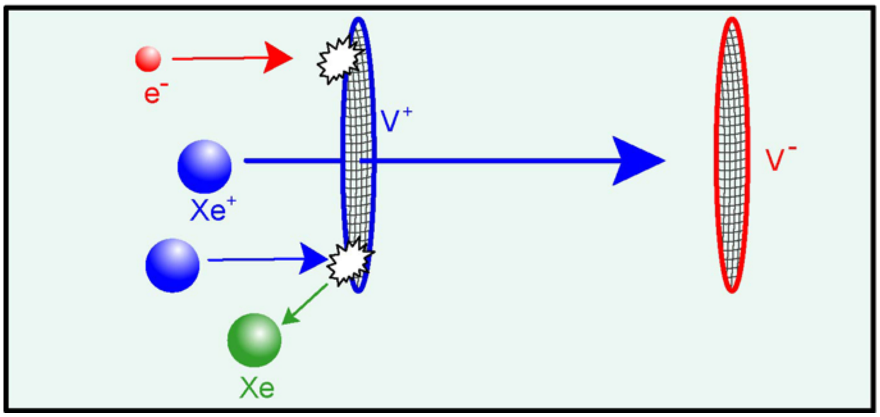
Second, xenon's first ionization energy, the energy required to remove one electron from a xenon atom, is 12.1 kJ/mol or 0.125 eV/atom. This is a low first ionization energy for a inert gas, although it is relatively high when compared with other elements. [An electron volt (eV) is the energy that a particle of one electronic charge acquires from falling through a potential difference of one volt, which is equal to 1.6×10^{-19} joule.]

Third, the exhaust velocity is related to the charge-to-mass ratio of the ions. Xenon 1+ ions, with an atomic mass of 131g/mol, have a high charge-to-mass ratio (7.14×10^5 coul./kg).

2. Attraction to an electrically-charged grid

The function of the two electrically-charged electrodes at the rear of the Dawn ion engine is to move xenon ions in the same plane and accelerate them. The first grid encountered by a xenon ion is labeled V^+, which indicates that it is positively-charged *relative to* the second grid at the rear of the engine, labeled **V^-**. However, it is more negative than the walls of engine and the xenon ions. So, in keeping with graphically showing smaller charges as being smaller, the first grid is shown below with a very thin blue line. This ***does not mean*** that the V^+ grid itself is physically thinner than the V^- grid.

Since the first grid is slightly negative to the xenon ions, they are drawn toward it. The grid moves the ions in the correct plane and increases the chance of the ions going through the grid by increasing the effective surface area of the hole. Once near the first grid, the ion "sees" the great potential difference between the first and second grid and is accelerated to very high speeds. There is a lensing effect by the electric field on the grid that also helps improve the chances of the ion making it through the holes in the grid.



The wide blue arrow in this graphic indicates that our xenon ion is now a part of a very directionalized stream of ions going through the first grid. This ion stream is sometimes referred to as a thrust beam or plasma stream.

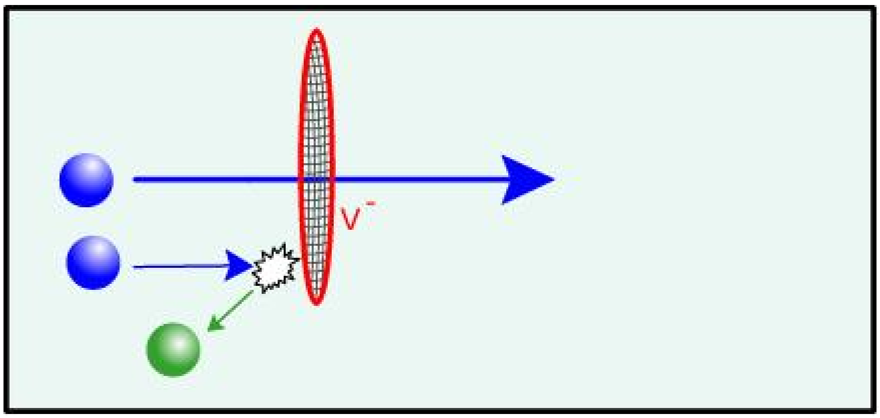
Negative electrons that were not attracted to the engine walls can be attracted to the grid and are discharged when they strike it, as indicated by the white flash .

Occasionally a xenon ion strikes the grid, where it is neutralized (indicated by the white flash) and reforms a xenon atom. If that atom is to contribute to the engine's thrust, it must then be re-ionized by another collision with an electron.

3. Acceleration toward the second electrically-charged grid

The second electrode, **V⁻**, is located only about 1000 micrometers (μm), which is the width of 10 human hairs, away from the first electrode. It is more negative than the first by 1,280 volts so it is shown with a thicker line than the first electrode. This grid exerts a strong electrostatic pull on the xenon ions, accelerating them toward the grid. Our xenon ion acquires a speed of 35,000 m/s as it is accelerated through the width of 10 human hairs between the two grids! This change in momentum is transferred to the spacecraft if the ion passes through a hole in the last grid.

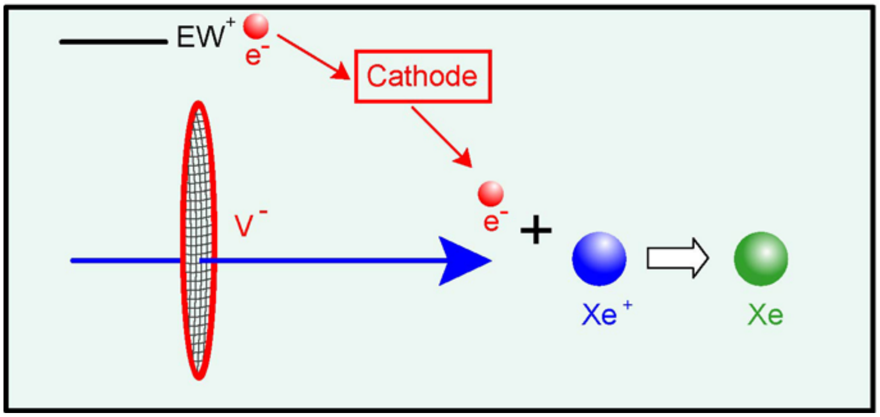
According to Newton's Third Law, the reaction force of the accelerating xenon ions moving toward the back of the engine **accelerates the grid (which is attached to the spacecraft) forward** with an equal but opposite thrust—1/50th of a pound (92milliNewtons) of thrust. This is the amount of force roughly equal to the force you feel when a piece of printer paper is placed on your outstretched hand.



If our single xenon ion is the only ion between the two grids, it would have a clear path to the negatively-charged grid. However, we have already said that our ion is part of a positively-charged plasma stream. Since each of these ions forms an electric field that repels our ion, these other ions in the "crowd" could also "shield" our ion from the full attractive force of the grid if they are between our ion and the grid. This interaction of positive ions can lower the engine thrust if the space between the grids is so large that too many ions are in the space at the same time.

If the xenon ion collides with the grid, it applies a force that slows down the spacecraft. This is why it is important for the ion to move through the holes in the last grid.

4. Neutralization of the xenon ion



Remember that electron that was removed from the xenon atom during the ionization process? Well, that electron (and others resulting from the ionization of xenon atoms) has moved from the chamber walls to a cathode toward the rear of the engine. Shortly after moving through the second grid, but before the beam leaves the engine, the xenon ion recombines with an electron released from the cathode, thus reforming a neutral xenon atom. This is important since the grid is negative. If the ion is not neutralized, it will stop and reverse its direction. This is even worse than having an ion stopped by hitting the grid because the change in momentum is much greater.

How do these very tiny xenon ions provide enough thrust to move the spacecraft? Thrust is the reaction force described by Newton's third law when a system accelerates mass in one direction to propel a vehicle in the opposite direction.

Although the mass of xenon ions is very small, their acceleration is so great that they are providing enough thrust to propel the Dawn spacecraft in the opposite direction. It's as if **the positively-charged xenon ions are pulling the negatively-charged grid toward them** with enough force to change the spacecraft's velocity about 7 x 10^{-5} m/s/s.

Mathematically expressed, the force of the ions $F_1 = m_1a_1$ equals the force on the spacecraft engine in the opposite direction, $F_e = m_ea_e$. So, $m_1a_1 = m_ea_e$, where a_1 represents the great acceleration of the xenon ions and m_e represents the large mass of the Dawn engine.