THE PLASMA CONNECTION

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Plasma Rockets

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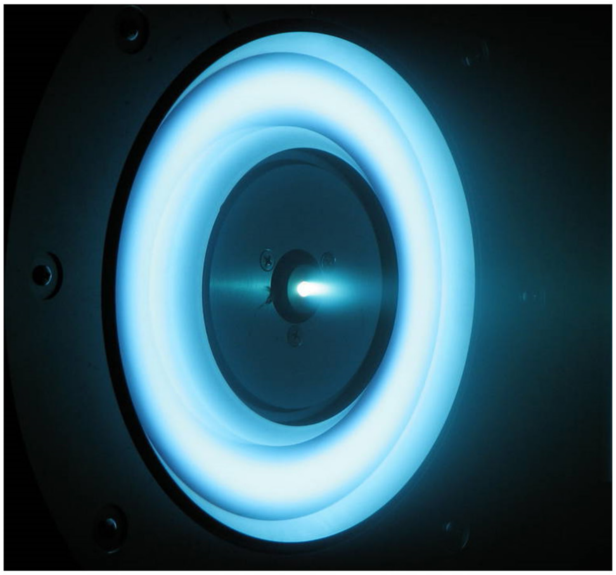
Plasma rockets are the fastest growing way to propel spacecraft. Their plasma is created using electrical energy to ionize a gas, so they are a part of the family of electric propulsion (EP). Plasma rockets are particularly popular with spacecraft designers because they are over ten times more propellant efficient than conventional chemical rockets that use hot gases. Due to the low propellant efficiency of chemical rockets, spacecraft often need to carry so much propellant that over half of the spacecraft mass is from the propellant. For example, to go from a Low Earth Orbit (LEO) to a Geosynchronous Orbit (GEO), Tsiolkovsky's famous rocket equation shows that a 1000 kg spacecraft could need over 2000 kg of propellant to perform its mission. By using high-efficiency plasma rockets, the same spacecraft could only need less than 200 kg of propellant. Therefore, by using plasma rockets, you could launch two or more spacecraft for the cost of one. Or, you could bring more propellant to do up to ten times the space mission such as deeper exploration into space, longer missions, and more maneuvers. Such capabilities are attractive as humankind becomes increasingly interested in missions to the Moon, Mars, and asteroids.

Now that we have established the main benefits of plasma rockets, we can discuss how they work and why they can achieve high propellant efficiency. First of all, the thrust produced by a rocket is proportional to the speed of the propellant as it leaves the rocket's exhaust. Chemical rockets, like those used for high-thrust applications such as launch vehicles and missiles, use hot gases to provide the energy needed to generate thrust. The speed of the exhaust gases is limited by the energy density of the propellants and the allowable temperature of the system. Therefore, the speed of the exhaust from chemical rockets is limited to no more than about 5 km/s, which corresponds to specific impulse, I_{sp}, of less than 500 seconds (note: I_{sp} is the way rocket engineers denote propellant efficiency using units of seconds). In contrast, plasma rockets use electromagnetic fields to accelerate the ions of a plasma to speeds that can exceed 50 km/s, yielding I_{sp} values over 5000 seconds. Because the exhaust velocity from plasma rockets can be on the order of ten times greater than chemical rockets, plasma rockets can get much more thrust for each atom or molecule of propellant, leading to high propellant efficiency. However, as discussed later, plasma rocket thrust levels are much lower than those typically provided by chemical rockets; this means the choice of rocket depends on the many needs of the mission such as desired thruster performance, mission objectives, and mass.

The most commonly used plasma rocket is the Hall effect thruster (HET). HETs use an ingenious design to generate a plasma in an annular channel. We will use the high-power NASA HET shown in Figure 1 to describe the process. First, the center-mounted cathode supplies negatively-charged electrons that are electrostatically attracted to the positively-biased anode, which is located in the back of the annular channel and is biased hundreds of volts above the cathode. Before these electrons can make it to this anode, they are trapped by a strong radial magnetic field near the downstream end of the channel. This creates a "Hall current" of these trapped electrons that propagates azimuthally around the channel; hence the name for the Hall effect thruster. These trapped electrons collide with and ionize the neutral propellant atoms flowing in from the anode region, creating positively-charged ions and the beautiful glow of the annular plasma. These ions (typically xenon or krypton) are over 100,000 times the mass of the electrons, so the magnetic field that traps the electrons is not strong enough to trap these ions. Therefore, the electric field that is pulling the electrons towards the anode at the back of the channel instead pushes these ions out of the channel. This creates thrust with ion speeds typically on the order of 15 to 20 km/s, yielding I_{sp} values of about 1500 to 2000 seconds. HETs have been flown since the 1970s but have recently seen a large increase in use as the primary propulsion



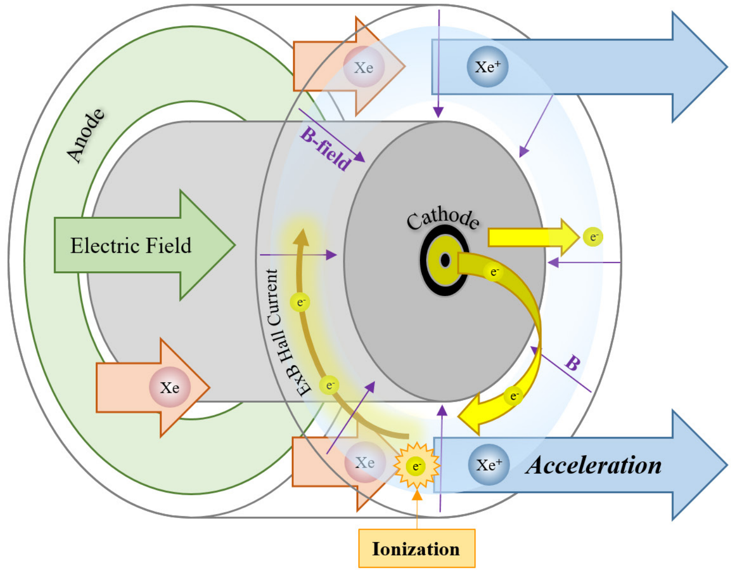
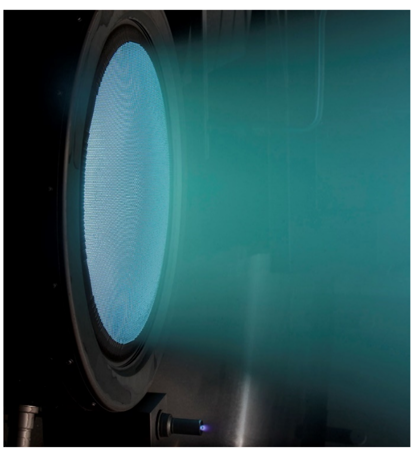


Figure 1: 6kW Hall Effect Thruster (left, NASA); HET Operating Principles (right, Wirz)



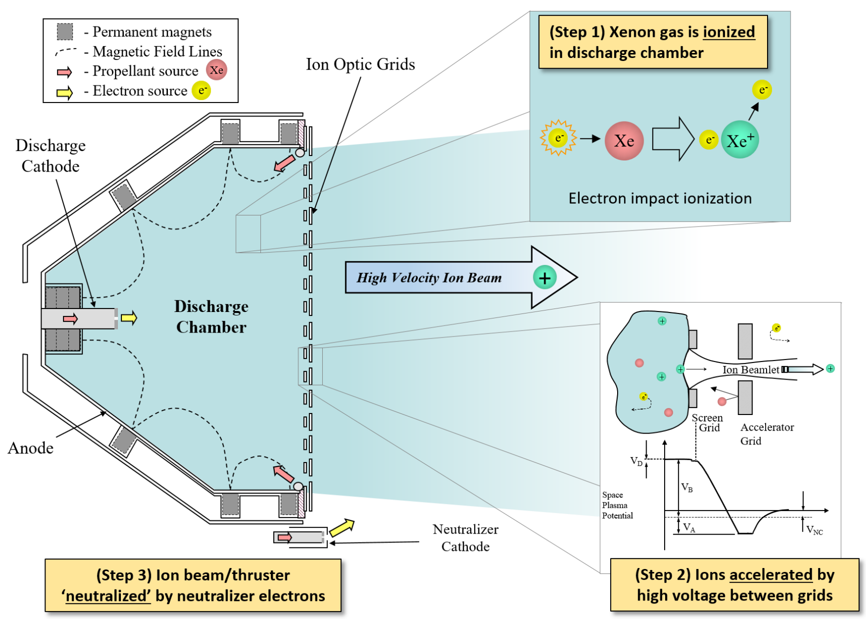


Figure 2: NEXT Gridded Ion Thruster (left, NASA); GIT Operating Principles (right, Wirz)

for SpaceX's growing Starlink megaconstellation, which as of January 2022 has launched more than 1,900 Starlink satellites with krypton-fueled HETs and hopes to have as many as 42,000 satellites in orbit at full capacity.

For even higher propellant efficiency, rocket engineers can use another plasma rocket called a gridded ion thruster (GIT). GITs create high velocity ions in a two-step process as shown in Figure 2. First, electrons from a cathode are accelerated to the anode walls of a discharge chamber. These electrons are trapped by a magnetic field that allows the electrons to reside in the chamber long enough to ionize the propellant, typically xenon, and create a plasma. The second process is to use a set of precision-aligned grids to apply thousands of volts (typically 1000 to 2000 V) to electrostatically accelerate the ions to velocities over 30 to 50 km/s, yielding I_{sp} values of about 3000 to 5000 seconds.

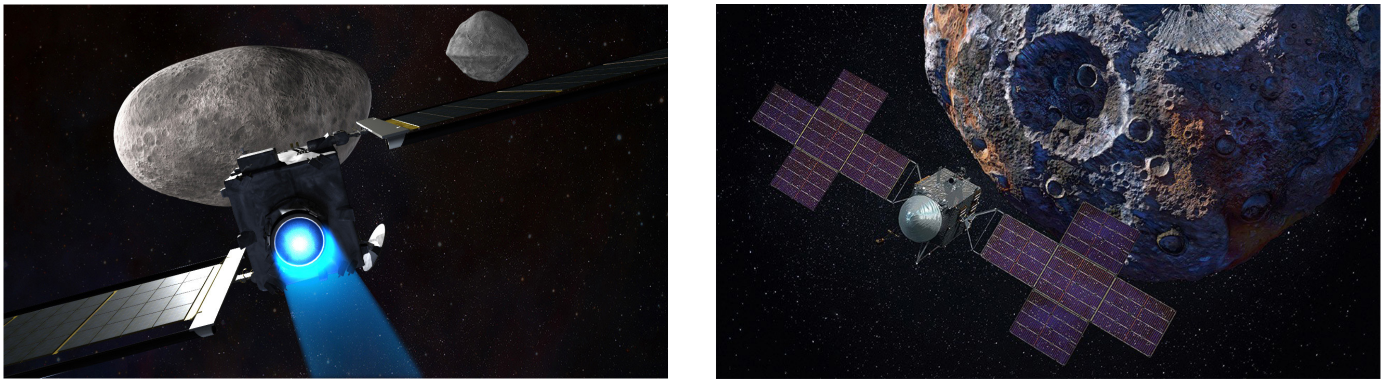


Figure 3: (Left) Artist's depiction of the DART spacecraft using a GIT plasma rocket to redirect Dimorphos, which is orbiting the larger Didymos in the background. (Right) The Psyche mission that will use HETs to explore the metal-rich Psyche asteroid. (Images: NASA)

A common question is, "Why aren't plasma rockets used for launch?" To understand why, we will introduce a the simplest equation used in rockets: the "Thrust Equation", where thrust is equal to the product of mass flow rate and exhaust velocity, or simply, *Thrust=mass flow rate × exhaust velocity*. Chemical thrusters can achieve high thrust by using extremely high mass flow rates; hence, thrust is predominantly dictated by the rate at which you can pump fuel and oxidizer into the combustion chamber and out of the nozzle. In this way, launch vehicles use chemical thrusters to process many gigawatts (billions of watts) of thrust power to generate the millions of pounds of thrust force needed for most launches. On the other hand, plasma rockets can only process so much power, which is typically less than 10 kilowatts for HETs and GITs currently in space, resulting in thrust levels typically less than a newton. If you did build plasma rockets powerful enough to process gigawatts of power, they would likely be prohibitively heavy and, most importantly, would also need to somehow carry or receive gigawatts of electric power during launch. So, it is safe to say that, for the foreseeable future, chemical rockets are our best option for higher thrust applications such as launch while plasma rockets continue to grow in use for lower thrust in-space propulsion.

HET and GIT plasma rockets are already being used for many Earth-orbiting missions in LEO and GEO. They have also enabled ambitious asteroid missions such as NASA's Deep Space One (DS-1), DAWN, Double Asteroid Redirection Test (DART), and soon-to-be-launched Psyche, as well as the Japan Aerospace Exploration Agency (JAXA) asteroid sample return missions Hayabusa and Hayabusa2. The future of plasma rockets is the development of higher-powered thrusters for larger robotic and human missions, as well as the development and use of lower-powered thrusters for miniature satellites and precision control of larger spacecraft. Future plasma rockets may use high power density designs such as magnetoplasmadynamic thrusters (MPDTs) or even fusion thruster concepts. Whatever the future holds, with the rapid increase in use and development of space electric propulsion and power, the future is bright for plasma rockets.

Suggested Reading:

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Text and Diagrams provided by R. E. Wirz; Images provided by NASA; Edited by M. Laroussi

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