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# The VASIMR

by Franklin R. Chang Díaz

**W**e dream of going to the stars. As young children growing up in the 1950s, my friends and I were awestruck by the possibility of space travel. As I have learned over the years, our fascination was not unique to my Costa Rican upbringing. Indeed, many of my co-workers today, coming from different parts of the globe, recount similar childhood longings. In the past 50 years, I have had the opportunity to witness the development of the first ships that have transported humans beyond Earth. In the past 20, I have been fortunate to ride on some of these rockets and to get a firsthand glimpse of wonders I could only imagine before. It would seem as if we are destined to burst off our fragile planet and move into the cosmos in a new human odyssey. Such a mighty undertaking will dwarf the westward European expansion of the 16th century.

PAM FRANCIS

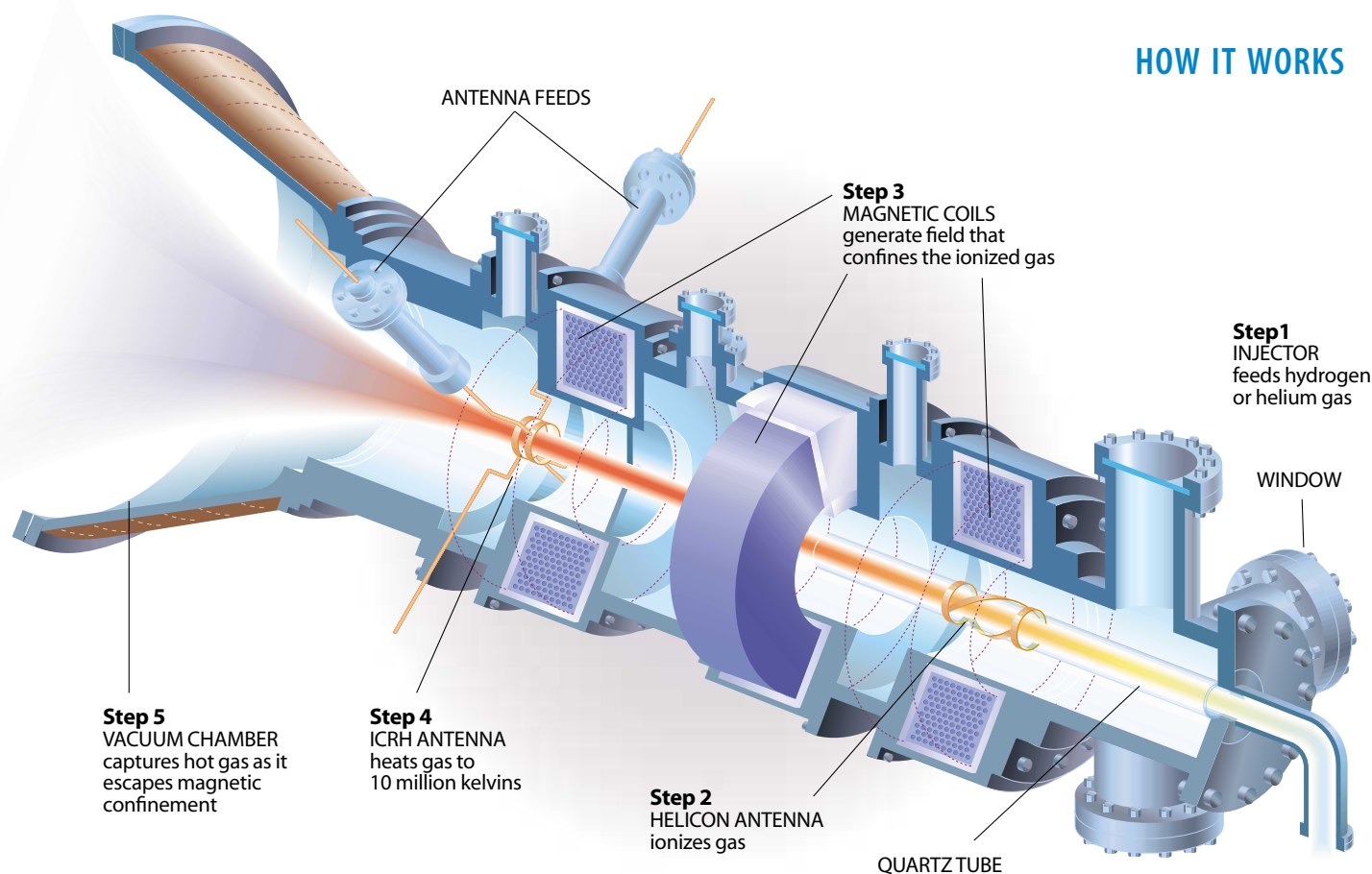


**RADICALLY NEW ROCKET** engine, just three meters long, produces an exhaust of unprecedented speed: 300 kilometers per second. The window on the right reveals the glowing plasma inside. For a cutaway view, see page 92.



There used to be two types of rocket: powerful but fuel-guzzling, or efficient but weak.  
Now there is a third option that combines the advantages of both





Yet we lack the ships required to venture far into the vastness of space. With today's chemical rockets, a trip to Mars would take up to 10 months in a vulnerable and limited spacecraft. There would be little room for useful payload. Most of the ship's mass would be taken up by propellant, which would be spent in a few short bursts, leaving the ship to coast for most of the journey [see "How to Go to Mars," by George Musser and Mark Alpert; *SCIENTIFIC AMERICAN*, March]. If people were to travel to Mars under these conditions, their bodies and minds would suffer considerably. Months of exposure to weightlessness would weaken their muscles and bones, and the persistent radiation of outer space would damage their immune systems.

To be safe, human interplanetary spacecraft must be fast, reliable and able to abort in the event of malfunction. Their propulsion systems must be capable of handling not just the cruise phase of the journey but also the maneuvering near the origin and destination planets. Whereas chemical propulsion can continue to provide excellent surface-to-orbit transportation, new technologies are required to send humans to the planets and ultimately to the stars.

Plasma rockets are one such technology. Utilizing ionized gases accelerated by electric and magnetic fields, they increase performance far beyond the limits of the chemical rocket. My research team has been developing one of these concepts, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR), since the early 1980s. Its genesis dates back to the late 1970s, when I was involved in the study of magnetic ducts and their application to controlled nuclear fusion. In such ducts, a magnetic field insulates a hot plasma from its nearest material surface, letting it reach temperatures of hundreds of millions of degrees Celsius.

I theorized that a duct, properly shaped, could form a magnetic nozzle and convert the plasma energy to rocket thrust. Such a structure functions like a conventional rocket nozzle but can withstand much higher temperatures. Further investigation suggested that the system could also generate a variable exhaust, adaptable to the conditions of flight, just as an automobile transmission matches the power of the engine to the needs of the road. Although the idea of variable exhaust dates to the early rocket pioneers, its implementation in chemical rockets with fixed ma-

terial nozzles has proved impractical. In VASIMR the concept is finally poised to become a reality.

### Newton's Rocket

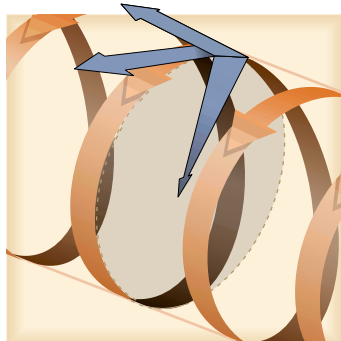
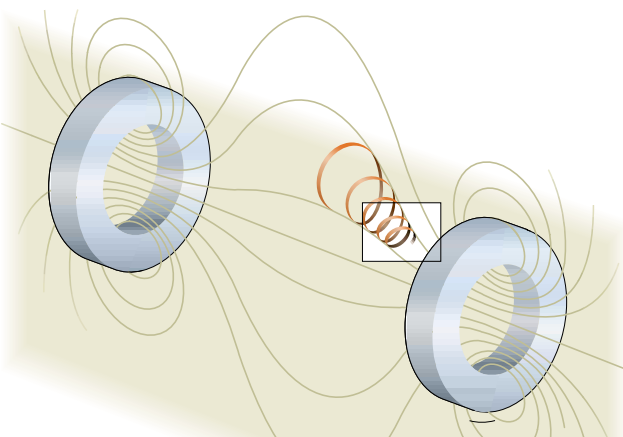
The principle of rocket propulsion stems from Newton's law of action and reaction. A rocket propels itself by expelling material in the direction opposite to its motion. The material is usually a gas heated by a chemical reaction, but the general principle applies equally well to the motion of a simple garden sprinkler.

Rocket thrust is measured in newtons and is the product of exhaust velocity (relative to the ship) and the rate of propellant flow. Quite simply, the same thrust is obtained by ejecting either more material at low velocity or less at high velocity. The latter approach saves on fuel but generally entails high exhaust temperatures.

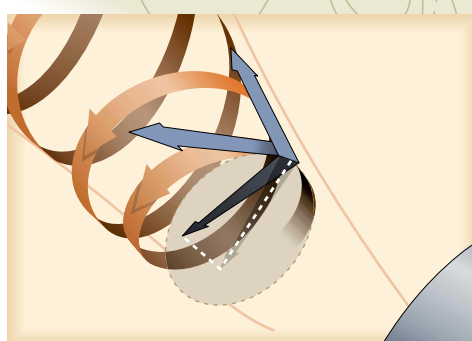
To gauge rocket performance, engineers use the term specific impulse ( $I_{sp}$ ), which is the exhaust velocity divided by the acceleration of gravity at sea level (9.8 meters per second per second). Although thrust is directly proportional to  $I_{sp}$ , the power needed to produce it is proportional to the square of the  $I_{sp}$ .



**MAGNETIC MIRROR** traps the particles so they can be heated to 10 million kelvins. It consists of two ring electromagnets that set up a bulging magnetic field between them.



Near the center of the mirror, the field lines are parallel, so the magnetic force is radial. Particles travel at a constant speed along a helix of nearly constant radius.



Near each magnet, the field lines tilt. A component of the force now pushes the particles away from the magnet. If the particles are moving toward the magnet slowly enough, they are stopped and reversed. In that region, the helix tightens.

Therefore, the power required for a given thrust increases linearly with  $I_{sp}$ . In chemical rockets this power originates in the exothermic reaction of the fuel and oxidizer. In others, it must be imparted to the exhaust by a propellant heater or accelerator. Such systems depend on a power source elsewhere in the ship. Solar panels are generally used; the abundant power requirements of human space exploration, however, will favor nuclear reactors [see box on page 97]. This is especially true for missions beyond Mars, where sunlight is relatively feeble.

In our quest for high fuel efficiency, hence high  $I_{sp}$ , my research team has moved away from chemical reactions, in which the temperature is only a few thousand degrees, and entered the realm of plasma physics, in which the temperature is high enough to strip the atoms of some (if not all) of their electrons. The temperature of a plasma starts at about 10,000 degrees Celsius, but present-day laboratory plasmas can be 1,000 times hotter. The plasma is a soup of

charged particles: positive ions and negative electrons. At these temperatures the ions, which have the bulk of the mass, move at velocities of 300,000 meters per second—60 times faster than the particles in the best chemical rockets.

Usually, by design, the power output of the engine is kept at a maximum, so thrust and  $I_{sp}$  are inversely related. Increasing one always comes at the expense of the other. Therefore, for the same propellant, a high  $I_{sp}$  rocket delivers a greater payload than a low  $I_{sp}$  one, but in a longer time. If a rocket could vary thrust and  $I_{sp}$ , it could optimize propellant usage and deliver a maximum payload in minimum time. I call this technique constant power throttling (CPT). It is similar to the function of an automobile transmission in climbing a hill or the feathering of a propeller engine in moving through the air.

One way to visualize CPT is by considering the way in which the ship acquires kinetic energy from the exhaust. If this process were totally efficient, the exhaust particles (viewed by a ground

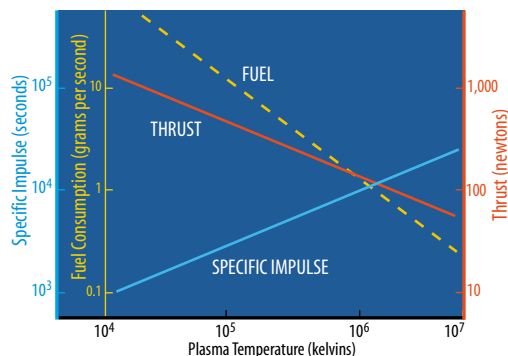
observer) would leave the ship at rest; the ship would be moving at the exhaust speed. All the exhaust energy would have been given to the ship. Thus, for a slow ship, an appropriately slow exhaust better utilizes the power source. As the ship speeds up, a faster (hotter) but leaner exhaust gives better results. Under CPT, the ship starts at high thrust for rapid acceleration. As its speed increases,  $I_{sp}$  gradually increases and thrust decreases for greater fuel economy. A car does exactly the same thing when it starts in low gear and steadily shifts up.

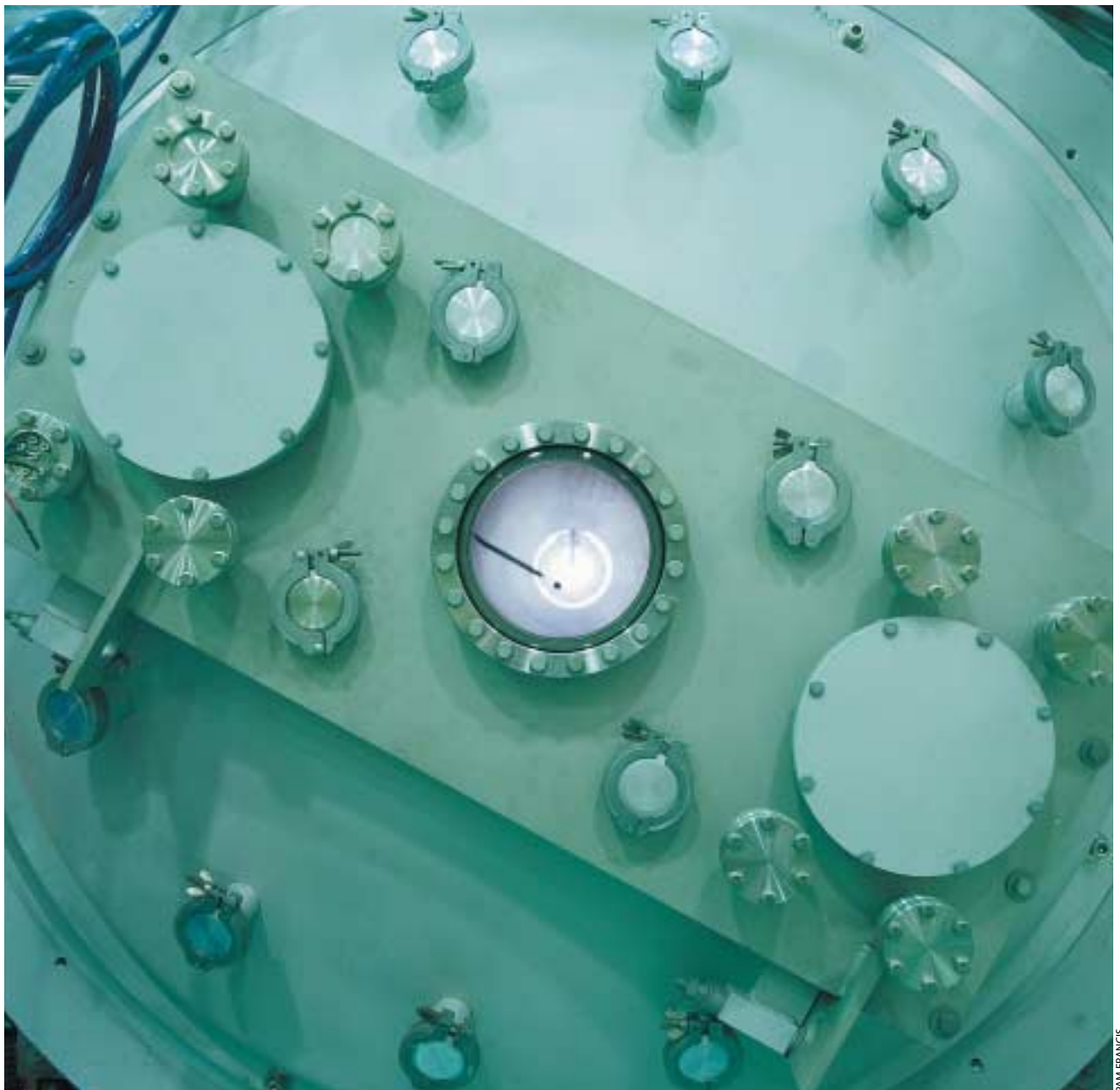
### Bouncing Back and Forth

VASIMR embodies a class of magnetic ducts called magnetic mirrors. The simplest magnetic mirror is produced by two ring electromagnets with current flowing in the same direction. The magnetic field is constricted near the rings but bulges out in between them. Charged particles move in a helix along field lines, orbiting around them at a specific radius, the Larmor radius, and at the so-called cyclotron frequency. As one might expect, for a field of a given strength, the heavier particles (the ions) have a lower cyclotron frequency and larger Larmor radius than the light ones (the electrons) do. Also, strong fields lead to a high cyclotron frequency and small Larmor radius. In VASIMR, the ion cyclotron frequency is a few megahertz (MHz), whereas its electron equivalent is in the gigahertz range.

The particles' velocity has two components: one parallel to the field (corresponding to the forward motion along the field line) and the other perpendicular (corresponding to the orbital motion around the line). When a particle approaches a constricted (hence stronger) field, its perpendicular velocity increases, but its parallel one is reduced proportionately to keep the total energy

**LIKE A CAR GEARSHIFT**, and unlike other rockets, VASIMR can adjust its output. By increasing its temperature, it boosts its specific impulse (blue) and reduces fuel consumption (yellow)—at the price of less thrust (red). The power is constant 10 megawatts.





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**LOOKING DOWN THE BARREL** of the rocket, you see the plasma coming straight at you. The window is 15 centimeters across.

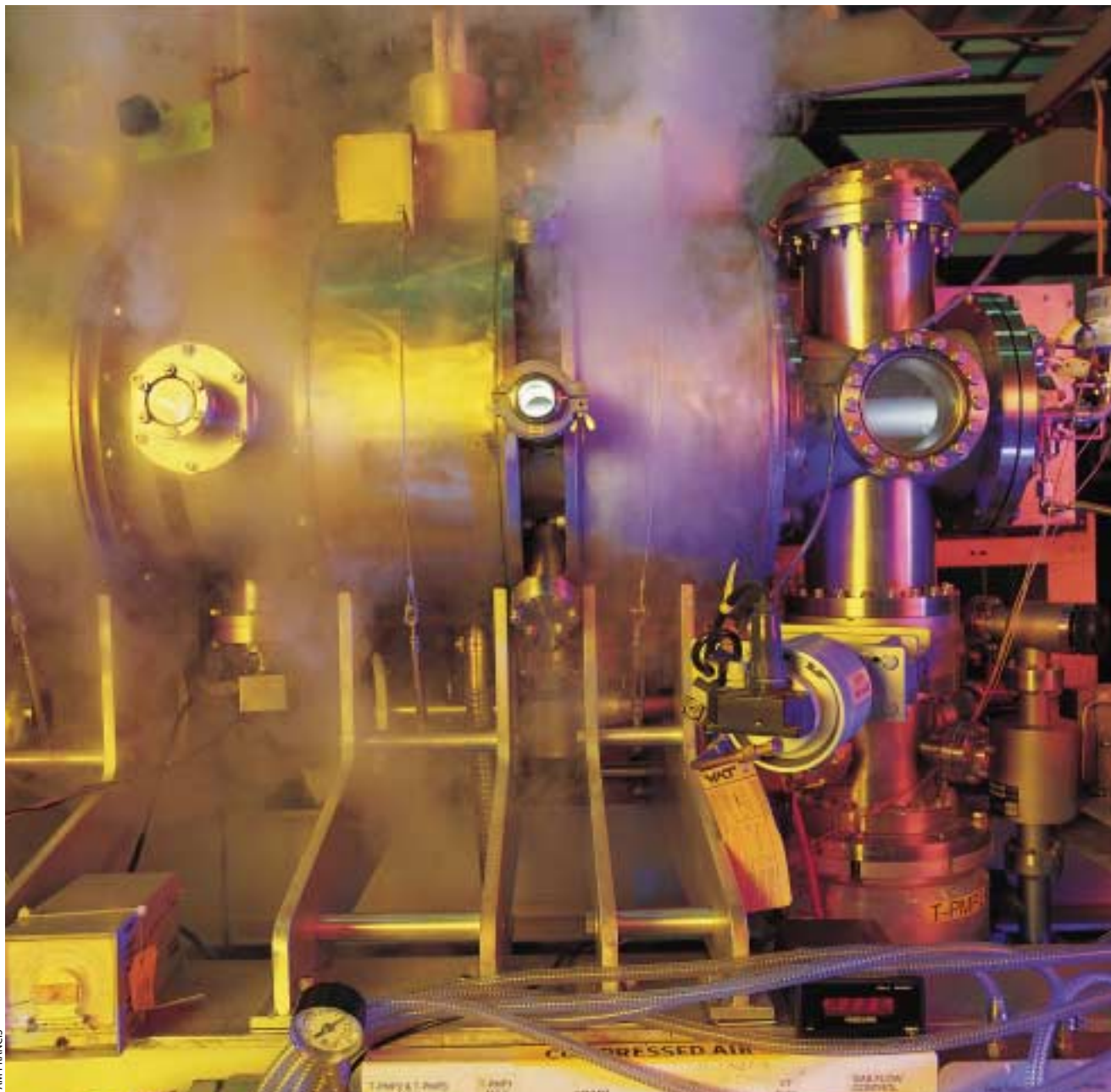
constant. The reason has to do with the direction of the force exerted by the field on the particle. The force is always perpendicular to both the particle's velocity and the field direction. Near the center of the mirror, where the field lines are parallel, the force is radial and so has no effect on the parallel velocity. But as the particle enters the constriction, the force tilts away from the constriction, resulting in an imbalance that decelerates the particle [see *top illustration on preceding page*]. If the particle is exiting the constriction, the field has the opposite effect and the particle accelerates. Because no energy has been added, the

acceleration comes at the expense of rotational motion. The magnetic field does no work on the particle; it is simply a vehicle enabling this energy transfer.

These simple arguments hold as long as the field constriction is slow and gradual compared with the particle motion—a condition known as adiabaticity. In their curling motion around the field lines, the particles are guided by them, but like fast-moving vehicles on a slippery highway, they can follow only lines that do not curve sharply.

A magnetic mirror can trap particles if they are sufficiently slow to be reflected at the field constrictions. The particles

bounce between them until something disrupts their parallel velocity such that it overcomes the trap or until one of the constrictions is reduced. With enough parallel velocity, the particle will push through and accelerate on the other side. Sudden changes in the velocity of a trapped particle, which may be enough to untrap it, can be brought about by random events such as collisions with other particles, interaction with electromagnetic waves, or plasma instabilities and turbulence. The magnetic field of Earth is a natural mirror. Charged particles from the ionosphere bounce back and forth between the North and South



PAM FRANCIS

**BILLOWING CLOUDS OF WATER VAPOR** pour off the magnets, which are kept at liquid-nitrogen temperature.

Poles. Some of them penetrate deep into the upper atmosphere, creating the spectacular auroras seen at high latitudes. VASIMR uses three such magnetic structures, linked together: a forward plasma injector, which ionizes the neutral gas; a central power amplifier, which energizes the plasma; and an aft magnetic nozzle, which finally ejects it into space.

#### Beam in the Power

Most plasma rockets require physical electrodes, which erode quickly in the harsh environment. In contrast, VASIMR uses radio antennas. The radio

waves heat the plasma just like a microwave oven heats food. Two wave processes come into play. First, neutral gas in the injector stage becomes a dense and comparatively cold (about 60,000 kelvins) plasma through the action of helicon waves. These are electromagnetic oscillations at frequencies of 10 to 50 MHz, which, in a magnetic field, energize free electrons in a gas. The electrons quickly multiply by liberating other electrons from nearby atoms in a cascade of ionization. Although the details are poorly understood, helicons are widely used in semiconductor manufacturing.

Once made, the plasma flows into the

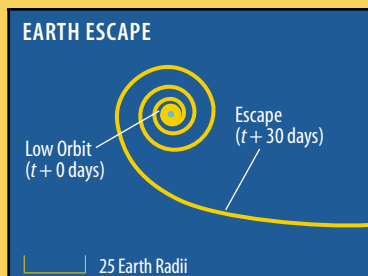
central stage, where it is heated by further wave action; the waves of choice here, however, are slightly lower-frequency ion cyclotron oscillations, so named because they resonate with the natural rotational motion of the ions. The wave's electric field is perpendicular to the external magnetic field and rotates at the ion cyclotron frequency. The resonance energizes the perpendicular motion of the particles. This effect, known as ion cyclotron resonance heating (ICRH), is widely used in fusion research. The central stage is ultimately responsible for the high  $I_{sp}$  of the rocket.

One might wonder how a boost in

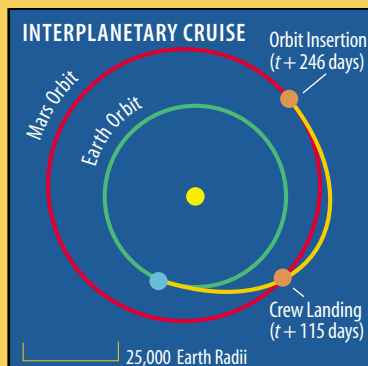


## MARS TRAJECTORY

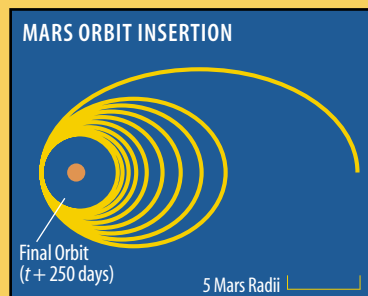
To get to Mars, the ship must first break free of Earth's gravity. Using low gear (maximum thrust and an  $I_{sp}$  of 3,000 seconds), VASIMR builds up speed.



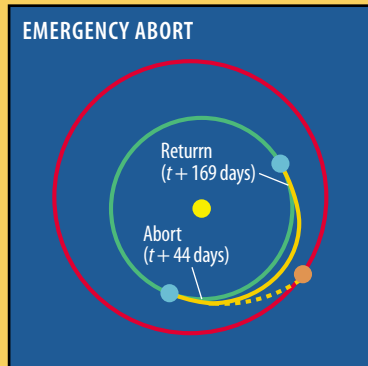
Unlike ordinary rockets VASIMR never coasts. It shifts to higher gears, reaching an  $I_{sp}$  of 30,000 seconds 75 days into the flight, and then starts to decelerate.



After flying by Mars to drop off the astronauts, the ship lowers itself into orbit.



VASIMR can turn around if something goes wrong early in the cruise.



the ions' perpendicular motion could impart any useful momentum to the rocket exhaust. The answer lies in the physics of the magnetic nozzle, the final stage of VASIMR. The diverging field here transfers energy from the perpendicular motion to the parallel motion, accelerating the ions along the exhaust. Being much more massive, the ions drag the electrons along, so the plasma exits the rocket as a neutral fluid. In VASIMR, this nozzle expansion occurs over a distance of about 50 centimeters.

Once the expansion is complete, the plasma must detach from the rocket. Recent studies by Roald Sagdeev of the University of Maryland and Boris Breizman of the University of Texas highlight the basic physics. The model involves the Alfvén speed, named after Swedish physicist Hannes Alfvén, who first described it. Disturbances in a magnetized plasma propagate along the field at this speed. In a magnetic nozzle, the Alfvén speed plays a role similar to that of the sound speed in a conventional nozzle.

The transition from sub-Alfvénic to super-Alfvénic flow delineates a boundary beyond which the flow downstream has no effect upstream—which ensures that the detachment exerts no drag on the rocket. The VASIMR nozzle is designed to expand the plasma past this boundary, to a point where the energy content of the field is small compared with that of the plasma flow. The plasma then breaks free, carrying with it a small amount of the field. A similar behavior is thought to occur in nature when solar flares detach from the magnetic field of the sun. The energy expenditure in the field distortion only minimally taxes the performance of the rocket. Our studies show that plasma detachment occurs one to two meters away from the nozzle throat.

### Partitioning the Power

The throttling that makes VASIMR distinctive is done mainly by changing the relative fraction of power going to the helicon and ICRH systems. For high thrust, power is routed predominantly to the helicon, producing more ions at lower velocity. For high  $I_{sp}$ , more power is diverted to the ICRH, with concomitant reductions in thrust. We are also studying two other exhaust variation techniques, including a magnetic choke at the nozzle throat for high  $I_{sp}$  and a plasma afterburner for high thrust at very low  $I_{sp}$ .

A key consideration is the efficiency of the engine over its operating range. Creating a hydrogen plasma costs about 40 electron volts per electron-ion pair. (An electron volt, or eV, is a unit of energy commonly used in particle physics.) This energy expenditure is not available for propulsion; most of it is frozen in the creation of the plasma. The particles' kinetic energy, which is what ultimately generates the thrust, must be added to this initial investment. In the early prototype of VASIMR, at high  $I_{sp}$ , the kinetic energy is about 100 eV per ion. Thus, a total energy expenditure of 140 eV yields 100 eV of useful energy, or about 70 percent efficiency. Later VASIMR designs will reach exhaust energies of 800 to 1,000 eV for the same initial investment, leading to greater efficiency. At low  $I_{sp}$ , as more plasma is generated for higher thrust, the kinetic energy per particle gets uncomfortably close to the ionization energy, with consequent reductions in efficiency. In the end, however, efficiency must be evaluated in the context of the overall mission. Sometimes brief bursts of high thrust may in fact be the most efficient approach.

The gas ionization involves other inefficiencies. Neutral atoms lingering in this initial plasma cause unwanted power losses if they remain mixed with energetic ions. In an effect known as charge exchange, a cold neutral atom gives an electron to a hot ion. The resulting hot neutral is oblivious to the magnetic field and escapes, depositing its energy on nearby structures. The cold ion left behind is virtually useless.

To avoid this, we are studying a radial-pumping technique, in which the cold neutrals are siphoned out before they wander into the power-amplification stage. They may be reinjected downstream of the nozzle throat, where the ions are already moving in the right direction and charge exchange actually helps the plasma to detach from the rocket. Charge exchange is a serious problem in fusion research today.

Although the helicon is able to ionize nearly any gas, practical considerations favor light elements such as hydrogen and helium. For example, the ICRH process is easiest in light gases, whose cyclotron frequencies at reasonable fields (about one tesla) are compatible with existing high-power radio technology. Fortunately, because hydrogen is the most abundant element in our universe, our ships are likely to find an ample supply of propellant almost everywhere. An-



In space, power is life. In the spring of 1970 the *Apollo 13* astronauts managed to stay alive by judicious use of their precious battery power. Had their return flight taken longer, they would have met with disaster. The electrical requirements of human spaceflight are set by basic survival needs: rapid transportation and life support. The space shuttle consumes about 15 kilowatts in orbit; the International Space Station, 75 kilowatts. Estimates for a Mars habitat range between 20 and 60 kilowatts—not including propulsion. For a baseline Mars mission, a VASIMR engine would require about 10 megawatts. Higher power means faster transits. A 200-megawatt VASIMR would get to Mars in 39 days.

For human forays into near-Earth space, chemical fuels and solar panels provide sufficient power. But for Mars and beyond, chemical fuels are too bulky and the sun's rays too weak. A 10-megawatt solar array, for example, would be about 68,000 square meters at Mars and 760,000 at Jupiter. Such gigantic panels are impractical; in comparison, the solar panels on the International space station are 2,500 square meters. There is only one source: nuclear.

In the past, nuclear electricity has generally been obtained

from "nuclear batteries"—radioisotope thermoelectric generators (RTGs), which rely on the heat generated by the natural radioactive decay of plutonium. Such devices have proved crucial to robotic space missions but are too inefficient for human flight. Far better would be a nuclear reactor, which relies on the fission of uranium in a chain reaction. For each kilogram of fuel, a reactor produces up to 10 million times more power than an RTG does.

To measure the efficiency of power sources, space engineers use a parameter called alpha, which is the ratio of power plant mass to electrical output. Low alphas correspond to high efficiency and high power. Present solar arrays, operating near Earth, have alpha values of about 100. RTGs manage an alpha of 200. But for uranium reactors, alphas can be as low as 0.5.

Reactors are inherently safer than RTGs, because the reactor and fuel can be launched separately and assembled in an orbit far from Earth. Even critics who call for a ban on nuclear power in Earth orbit have acknowledged its importance for deep-space missions [see "Nuclear Power in Space," by Steven Aftergood et al.; *SCIENTIFIC AMERICAN*, June 1991]. —F.C.D.

other important engineering challenge is the generation of strong magnetic fields. We are investigating new high-temperature superconductors, based on bismuth strontium calcium copper oxide compounds. The magnets will use the cryogenic hydrogen propellant to cool them.

Early VASIMR experiments, which I began in the 1980s with Tien-Fang Yang and others at the Massachusetts Institute of Technology, have led to the present research program. The centerpiece today is the VX-10 prototype at the National Aeronautics and Space Administration Johnson Space Center in Houston. Two smaller experiments at Oak Ridge National Laboratory and the University of Texas support the investigations. We also have partnerships with Rice University, the Princeton Plasma Physics Laboratory, the University of Michigan, the University of Maryland and the University of Houston, as well as with private industry and with NASA centers in Huntsville, Ala.; Cleveland; Greenbelt, Md.; and Norfolk, Va.

We are now formulating plans to test VASIMR in space. A proposed mid-2004 demonstration involves a 10-kilowatt solar-powered spacecraft, which will also study Earth's radiation belts. In another test, a VASIMR engine will try to neutralize the atmospheric drag on the International Space Station. Recent experimental results and rapid progress in the miniaturization of radio-frequency equipment bode well for such space tests.

As a natural progression, a possible VASIMR human Mars mission involves a 12-megawatt system. The ship would climb on a 30-day outward spiral from Earth and cruise through interplanetary space for 85 more days, accelerating much of the way and then decelerating for arrival at Mars. The trip would be twice as fast as one involving chemical rockets. A crew module would detach and land using chemical rockets, while the mother ship would fly by the planet in a fuel-efficient trajectory to rejoin it four months later. To protect the human crew, the Mars vehicle would be

provided with a robust abort capability by virtue of its variable exhaust. Its magnetic field and the hydrogen propellant would act as a radiation shield.

VASIMR could serve as a precursor to the great dream of those of us in the space program: a fusion rocket. Such a ship would have 10 to 100 gigawatts at its disposal. Although controlled fusion remains elusive, the efforts to achieve it have been relentless and the progress steady. Future generations will use it for rapid access to the planets and beyond. We now find ourselves preparing the groundwork for achieving that vision. SA

### The Author

FRANKLIN R. CHANG DÍAZ was scheduled to make his first spaceflight on the ill-starred *Challenger* in January 1986, but at the last minute his team was moved up one flight. Since then, he has flown five missions, highlights of which include the deployment of the Galileo probe to Jupiter, the first two tests of space tethers and the final shuttle Mir docking. In addition to his astronaut career and his plasma research (in which he has a Ph.D. from the Massachusetts Institute of Technology), he has worked in mental health and drug rehabilitation programs.

### Further Information

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