III. Science

A Fusion Plasma That Can Drive a Rocket in Space

by Ned Rosinsky, M.D.

Introduction

Nov. 3—This is the fourth part of a four-part series on fundamentals of fusion and plasmas. Part I appeared in EIR *Vol. 51, Number 33, Aug. 23, 2024, and reviewed the basic units of mass, length, time, force, work, and energy. There was also an introduction to electricity and magnetism, including a discussion of the electromagnet. Part II appeared in* EIR *Vol. 51 Number 37, Sept. 20, 2024, and reviewed the use of electric currents, electric fields, and magnetic fields in the creation of vortex filaments, as a magnetic bottle to contain plasma in a fusion machine. Part III appeared in* EIR *Vol 51, Number 41, Oct 18, 2024, and reviewed the creation of vortex rings, as an alternative magnetic bottle.*

Fusion involves the combination, or "fusing," of the nuclei of atoms of relatively light elements such as hydrogen or helium with each other, to produce enormous amounts of energy. The energy is produced when two small atomic nuclei combine to make a larger nucleus, and the mass of the new nucleus and other possible byproducts is slightly less than the initial mass of the two nuclei which fuse. If the energy is measured in joules and the mass in kilograms, then the energy produced is 90 million billion times the change in mass, which is the square of the speed of light in meters per second. The raw materials for many types of fusion are available and low cost. The major problem is to bring nuclei together close enough and long enough for them to fuse. Atomic nuclei are positively charged, and positive charges repel each other.

The solution is to heat the fuel to high enough temperatures where some of the electrons separate from the atoms, leaving the positively charged ions, or bare nuclei—a state of matter called a plasma. Under these conditions the nuclei are moving rapidly and they will crash into each other, and in some cases fuse. The temperatures required are 100 million degrees Centigrade or higher, and this heat would destroy any ordinary solid container. But there are two possibilities for containment. First, a small pellet containing the fuel can be rapidly vaporized using lasers on all sides, causing the fuel to recoil suddenly into a small volume, heat up, and fuse. This was done recently at Lawrence Livermore National Laboratories, which was the first time that a fusion experiment "broke even"—produced more energy than was put in. Second, magnetic fields can be arranged to contain the fuel at high temperatures without the fuel touching the walls of the container; this is called a magnetic bottle.

Advantages of the Princeton Rocket Engine

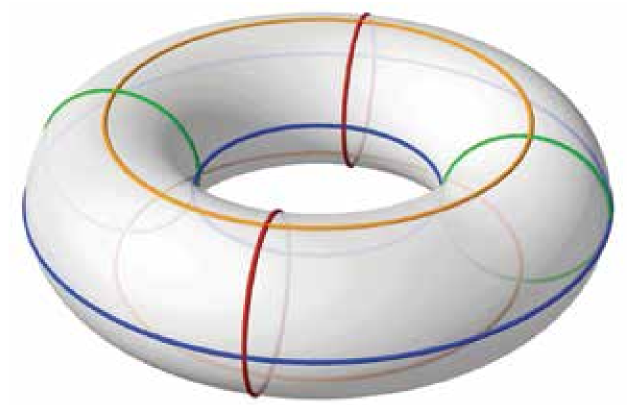
This article focuses on a particular magnetic bottle, a toroid-shaped magnetic field that contains a plasma in a stable condition, so that it can be heated to fusion temperatures. The Princeton Rocket Engine is being developed at Princeton Fusion Systems at Princeton University, and is described as a Field-Reversed Configuration because of the shape of the magnetic bottle and the contained plasma.

There are several advantages of the Princeton Rocket Engine, compared to other machines. It does not use neutral particles for heating, but relies on radiofrequency magnetic fields, which are safer for humans. It runs at a temperature high enough so that it can use fuels that do not produce neutrons, so it needs a much thinner and lighter shield, decreasing the weight for use in rockets. It is simpler in design, smaller, cheaper, and lighter than tokamaks, so five engines can be mounted on the same rocket, supplying redundancy in case of the failure of one or even two engines. Because smaller and lighter than other machines, it can be moved easily on a military HEMT truck for use on Earth in times of disaster or emergencies.

The development of the Princeton Rocket Engine is planned in 4 stages: PFRC-1, PFRC-2, PFRC-3 and PFRC-4. The current machine is the PFRC-2.

Magnetic bottles confine plasmas by causing the

FIGURE 1
The Torus



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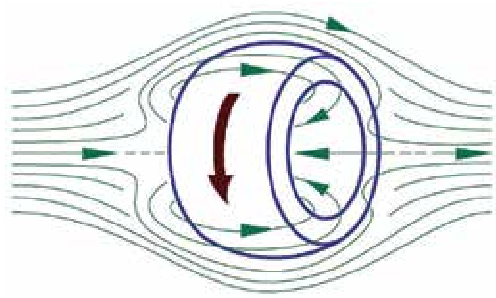
The torus is a donut-shaped surface. In this view, circles are drawn on the surface of the donut. A torus has two main directions when moving around on its surface, termed toroidal and poloidal. The blue circles are in the toroidal direction. The red circles are in the poloidal direction.

particles of plasma to move in circles or spirals, so they rotate within a confined area while they are being heated to fusion temperatures. These magnetic bottles are frequently shaped like a torus (**Figure 1**). The word "torus" refers to the surface of a shape which resembles a doughnut. Direction on the torus-shaped surface is described as "toroidal" for the long way around, and "poloidal" for the short way around, which is through the hole in the middle. The torus has a central axis which goes through the hole, perpendicular to the toroidal circular direction.

The term "toroid" is used when the torus is modified, as when the surface shape is filled in with matter on the inside such as by a plasma, or the shape is distorted by being stretched or twisted. An example of this kind of distortion would be a ring worn on the finger, which has a very narrow poloidal direction that is much shorter than the toroidal direction, and the poloidal shape is usually somewhat flattened, so the ring is comfortable between the fingers.

Princeton Fusion Systems is building a fusion rocket engine that uses a

FIGURE 2
How a 'Reversed Magnetic Field' Reverses



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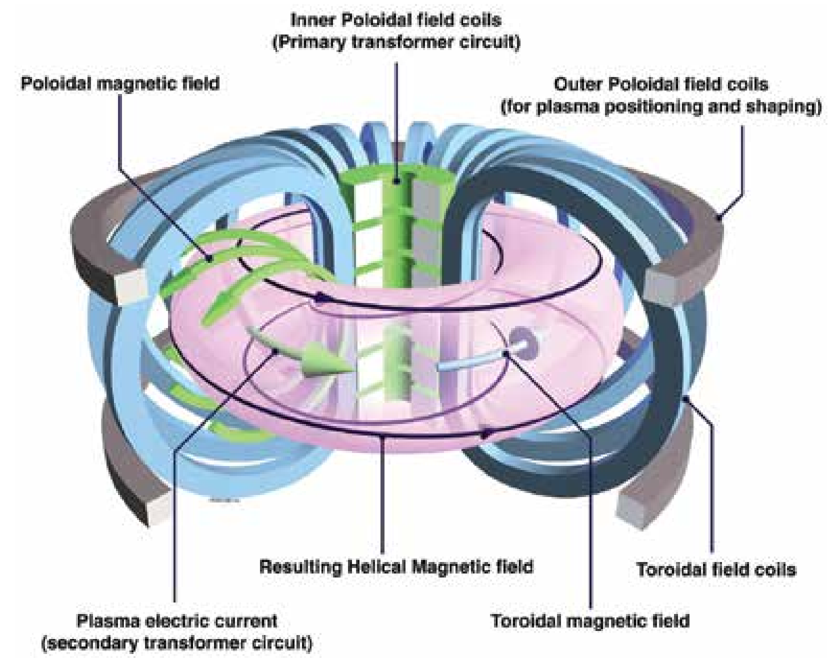
A toroid of current and plasma is shown, with the toroidal direction of rotation indicated by the large red arrow. A magnetic field produced by external coils (called the "bias field") extends from the far left to the far right, and goes around the outside of the toroid on all sides. The toroid's axis is parallel to the bias field. The toroid has created a second field around itself in the poloidal direction of rotation, which is parallel to the bias field on the outside of the toroid, but in the opposite direction inside the toroid. If this plasma toroid is extended in the left and right directions to form a long narrow toroid, shaped like a cylinder with thick walls, it approximates the shape of the toroid in the Princeton Field-Reversed Configuration.

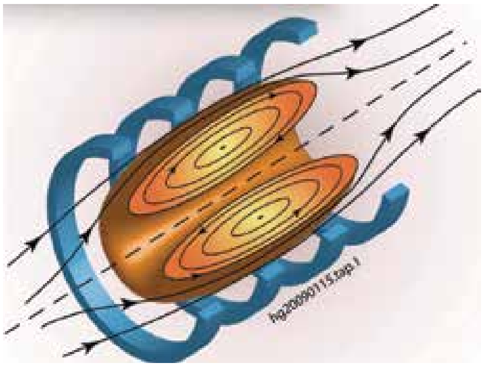
FIGURE 3
A Tokamak Experimental Fusion Machine



Li, H. Jiang, Z. Ren, C. Xu

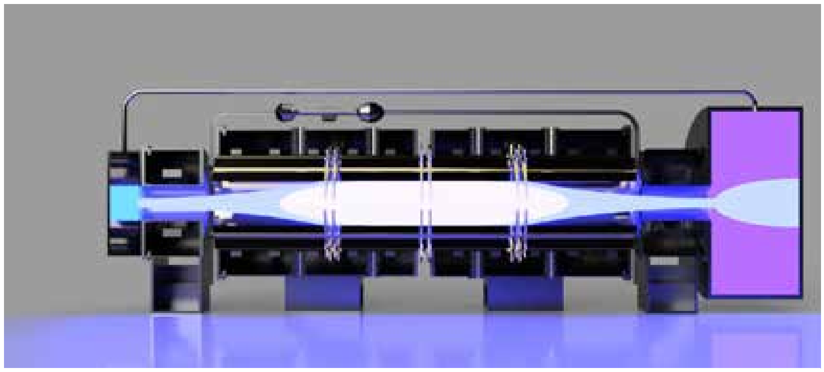
A tokamak has a toroidal chamber that encloses plasma. This chamber is surrounded by magnets, which supply both toroidal and poloidal fields to contain the plasma and keep it away from contact with the walls. The magnetic fields also cause the plasma to rotate around the toroidal chamber in a spiral, with both toroidal and poloidal components of the motion. The plasma is usually heated by beams of high energy neutral particles.

FIGURE 4
Cross-section of an Extended Toroid and Surrounding Coils



suli.pppl.gov

FIGURE 5
Model of Princeton Field-Reversed Configuration Fusion Reactor



Princeton Satellite Systems

The Princeton fusion rocket engine in cross-section. The long middle area contains a white cigar-shaped toroid area with rounded front and back ends. This toroid is the fusion fuel plasma. The plasma current is a toroidal sheath which revolves around the long axis. There are magnetic coils surrounding the plasma space, indicated in cross section as the black rectangles above and below the plasma. These magnetic coils create a solenoidal magnetic field parallel to the main axis of the plasma toroid, and this field is termed the "bias" field.

The horizontal thin lines above and below the plasma area are rectangular antennas seen from the side. These antennas emit radio frequency magnetic field radiation into the plasma, and thereby heat the plasma. Here the poloidal magnetic field is the long field, with field lines in the horizontal direction both inside and outside the plasma. The direction of the magnetic field that is outside the plasma toroid is parallel to the bias field, while the direction of the magnetic field inside the plasma toroid is in the opposite direction.

plasma toroid which is in the shape of a long pipe (**Figure 2**).

For controlled fusion, the magnetic bottle approach was started by the Soviet Union in 1952 with the Tokamak, which contains a hot plasma in a toroid-shaped thick-walled cylinder that is bent around so that the ends connect (**Figure 3**). The advantage of the Tokamak is that it can enclose hot plasma in a magnetic field and hold it away from the walls by circulating it around in a magnetic field, so the walls are not vaporized, which would contaminate the plasma. The disadvantage is that the rotating pathway close to the doughnut hole of the solid toroid is shorter than the pathways near the outer side surfaces, so the plasma does not circulate evenly, causing instabilities. There have been hundreds of variations on this solid toroid idea in machine experiments around the world, and although progress has been made, these problems have been difficult to solve thus far.

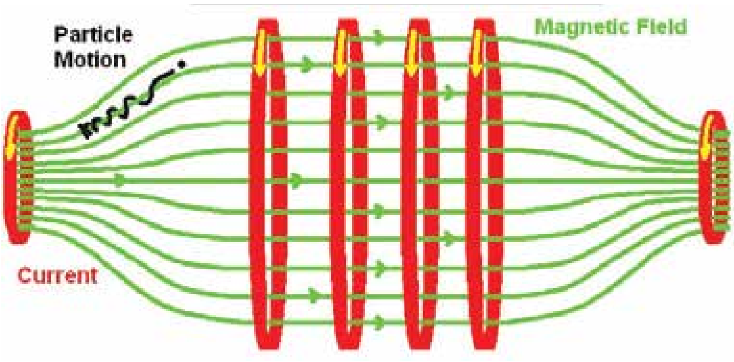
The Princeton Field-Reversed Configuration (PFRC) machine uses a straight cylinder to contain the fusion plasma. The first step in setting up the machine is to create a magnetic field inside the cylinder and parallel to the cylinder axis, using four solenoid field coils located outside the cylinder with wires wrapped around the cylinder (**Figure 4**), similar to the electromagnet initially described in Part I of this series. This initial magnetic field is termed the "bias" field.

The Magnetic Mirror Effect

The second step is to introduce warm heated plasma, pumped into the cylinder. In the PFRC-2, the plasma is derived from hydrogen gas. The plasma reacts to the magnetic field and forms a plasma toroid within the cylinder with a diameter of 16 cm, and with the toroidal rotation in a circle perpendicular to the axis of the cylinder (**Figure 5**). Thus, the plasma and current rotate perpendicular to the magnetic field. The toroid then elongates in the direction of the cylinder axis, forming an extended toroid in the shape of a cigar with a hole down the center, and with its length approximately 5 times its width.

There are two "mirror" magnetic coils, one at each end of the cylinder, which attempt to keep the plasma from leaking out of the ends of the cylinder. These mirror coils are much stronger than the other solenoidal field coils. This causes the magnetic field in the solenoid to become stronger at the two ends, which can be illustrated by the field lines bending and becoming closer to each other in a conical shape in the end regions.

FIGURE 6
A Magnetic Mirror



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A magnetic mirror consists of a cylinder, not shown, with relatively large solenoidal coils shown in red in this figure. These coils create a magnetic field, shown in green, parallel to the main axis of the cylinder, going from left to right. In this diagram, along the central part of the cylinder the coils have a moderate strength. At both ends, there are stronger coils that cause the magnetic field lines to curve inward toward the cylinder axis. On the upper left is the pathway of a particle, shown in black. Its spiral path tightens and shortens, until it reverses direction. This reversal of particle direction is the mirror effect.

Charged particles following these field lines will continue to follow them as the lines bend, but the effect is different from just following a bending magnetic field, because here the lines are getting closer to each other, *converging* while they are bending. The force of a magnetic field line acts perpendicularly to the particle path and to the field line, so the force will have a component which is perpendicular to the cylinder axis, and a component which is along the cylinder axis but opposite the direction of the particle along that axis. This will cause the component of the particle's motion parallel to the cylinder axis to slow, so that the overall *spiral* motion becomes *more circular with a shorter pitch* and has less motion down the cylinder axis.

At a certain point, the component of the particles' motion along the axis stops, so the motion is no longer a spiral; the particle has only circular motion. The magnetic mirror continues to have a component of force along the axis in the opposite direction than the particle was following, so the particle then reverses its motion along the cylinder axis, and the spiral axis then reverses to the opposite direction, towards the other end of the plasma cylinder. That reversal in direction is the mirror effect (**Figure 6**).

The mirror coils are effective for most of the particles, but some get through and escape out of the end of the cylinder, such as those which are travelling parallel or nearly parallel to the central cylinder axis, and which are located near the central cylinder axis when encountering the mirror, an area called the "escape cone." Particles that escape decrease the fuel and the energy content of the cylinder. This problem is addressed by the radio-frequency heating, as follows:

After the plasma is pumped into the cylinder and forms a toroid due to the magnetic field, the temperature of the plasma is significantly increased using energy from antennas that surround the cylinder. This is similar to a kitchen heater using microwaves, but the antennae's radio frequency (RF) is lower than microwave frequency. These antennas heat the plasma in the following ways.

First, the radio frequency waves used are at 2.4 megahertz (MHz), which is 2.4 million cycles per second. This frequency is close to the cycling frequency of the ions in the plasma around the plasma magnetic field lines. So the radio frequency couples with the ion motion, helping the plasma absorb the energy in the radio frequency waves. Think of pushing a child on a playground swing. If the swing has a natural back-and-forth cycle rhythm of 3 seconds, then you must time the pushes to the same 3-second frequency. If you push too early, the push will collide with the returning swing, and it will slow the swing down. If the push is too late, it will miss the swing.

Second, the direction vector of the radiation from the antennas is made to rotate around the plasma, by switching the radiation source from one of the surrounding antennas to another. There are eight antennas, each shaped like a rectangular picture frame, forming a ring of four antennas around the south pole half of the plasma toroid, and four around the north pole half. The antennas do not move, but in each group of four they take turns being on and off in sequence with some overlap, so not all are active at any one time. This rotation cycle is also at 2.4 MHz.

The direction vector of the radiation from each antenna is perpendicular to the axis of the cylinder. The rotating direction vector of the radiation creates a rotating magnetic field in the plasma, and this rotating magnetic field in the plasma creates an electric field that is perpendicular to the rotation; that is, parallel to the cylinder axis. This is related to the creation of a magnetic field from a rotating electric field as discussed above in the case of the electromagnet solenoid, and it is another basic relationship between electric and magnetic fields. This electric field which is transmitted through the plasma increases the speed of the plasma's charged particles, which heats the plasma.

Third, the magnetic antenna activity around one half of the length of the extended plasma toroid is timed to be coming from the opposite direction compared with the other half, so it is 180 degrees out of synchrony with the other half. This difference in direction is termed "odd parity" Rotating Magnetic Field Heating (RMF_o). In contrast, if the radiation direction were the same in the two halves, this would be termed "even parity" Rotating Magnetic Field Heating (RMF_e). Parity is a physics term that refers to the appearance of reflections in a mirror. If you hold both hands upright so that the palms are facing you, the left hand looks like a mirror image of the right hand, and that is even parity. If the left hand is reflected in a mirror at the top of the hand so the fingers are pointing down, the palm is still facing you, and the thumb is still on the outside, then that is odd parity.

The reversal of direction of the antenna field between the two plasma halves results in a sudden change in magnetic fields near the center of the machine, where the magnetic field is zero due to the change in direction there. This sudden change in field strength and direction causes significant acceleration in the charged particles, many of which travel in figure 8s between the two fields, and so it heats the plasma. The main heating pathway overall appears to be due to this effect of RMF_o radiation. Other FRC machines at other locations use RMF_e, which is not as effective.

Adding to this effect, the direction of the RMF_o radiation preferentially causes the particle motion to accelerate perpendicular to the cylinder axis, and also in the circulating direction around the axis. Only a few percent of the acceleration effect are directed along the axis. This limits particle motion towards the mirrors, and thus helps to confine the plasma.

Fourth, the heating effect of the antennas is related to the radiation wavelength, which is 125 meters, much longer than the distance of the antennas from the plasma. This can allow the transmission of a magnetic field directly into the plasma without the antenna emitting the usual photons that contain both electric and magnetic fields, so the field effect is more specific and effective.

A Reversed-Field Configuration

While the plasma within the cylinder is being heated as described above, the extended plasma toroid is strengthened by the increase in energy. This strengthened toroid itself creates a second magnetic field within the cylinder, in addition to the initial bias field which points from the front to the back end of the machine. The second magnetic field points from the front to the back of the machine in the area around the plasma toroid, but then loops around at the back end and travels through the hole in the plasma toroid in the opposite direction, from the back to the front of the machine. At the front, this second magnetic field leaves the end of the plasma toroid, and again travels toward the back of the machine around the toroidal plasma. This second field greatly helps to stabilize the plasma toroid.

Thus, the new field reverses the bias field along the extended hole of the plasma toroid, which is why this arrangement is called a "Reversed Field Configuration".

The strength of this new field can overwhelm the bias field in its direction along the extended hole due to the energy increase in the toroid from the RMF_o field.

In the final extended toroid, the ion and electron flow remain in a mostly toroidal direction, with some poloidal flow. The magnetic field created by the extended toroid is all poloidal.

For clarity, the term "toroid" is used for any modification of a torus that maintains one hole. This can include flattening, stretching or twisting. The term "toroidal" refers to a direction on the toroid, which loops around in the long direction and does not go through the hole. The term "poloidal" refers to a direction which loops around in the short direction and goes through the hole.

Now let us review the field-reversed configuration (FRC) as a sequence of currents and fields, as we did for the vortex filament and vortex rings.

Starting with the solid enclosing cylinder: There is rotating current in the surrounding magnetic coils, which we can call Current 1.

This current creates a magnetic field within the solid cylinder that is parallel to the cylinder, termed the bias field, and we can call this Field 1. Plasma is then pumped into the cylinder, which forms a toroid with the toroidal direction circulating around the solid cylinder axis, and this current is called Current 2. The circulating Current 2 is meanwhile heated by the two RMF_o magnetic fields that are out of sync, called Fields 3 and 4. The area where these two fields meet and change direction creates an enormous increase in the energy of the particles due to figure-8 pathways between the fields, which can be called Current 3.

Meanwhile, the increase in energy in the circulating Current 2 creates another magnetic field within the solid cylinder, which we can call Field 5. This field circulates in a poloidal direction around the extended current toroid, with the outside portion being outside the current toroid and the inside portion being through the extended hole in the toroid. The direction of this Field 5, outside the current toroid, is parallel to the bias field; inside the current toroid, it is opposite to the bias field.

Without detailing them, a further series of creations of magnetic fields and currents causes further heating of the plasma, and also further acceleration of the particles in the plasma. As plasma reaches the mirror coils at the end of the extended toroid, an additional electric field, conical in shape, is formed at the mirror coil, and particles emerge from it moving in the opposite axial direction.

Thus, the fields and currents in the FRC are added in an orderly sequence to form the final functioning fusion plasma. This can be considered as a "dialogue" form[1] of interaction, between fields and current flow.

Rocket Thrust

Rocket thrust is the propulsion of the rocket by heated gas exiting rapidly from the back of the engine. It is a force measured in Newtons. The Princeton engine is planned to be provided thrust by cold hydrogen or deuterium gas being introduced at the front of the engine, passing along the cylinder—between the cylinder wall and the plasma toroid, an area called the separatrix—and being heated by fusion from the plasma. This heating occurs due to radiation and hot particles produced by fusion, including tritium and helium-4.

The heated gas is gathered at the rear of the engine, where part of the energy is siphoned off to produce electricity to run the rocket. Contaminants are also removed while the energy is removed. The rest of the heated gas is shot out of the rear exhaust funnel to push the rocket forward.

To review: The reversed-field configuration (RFC) with rotating magnetic field heating (RMF_o) has several general advantages over other machines that do not use an RFC. It is four times more powerful than alternate fusion and fission powered engines. It has 100 times less neutron flow, which increases safety and requires a much lighter protective shield.

Specifically for use as a rocket engine, the Princeton FRC is smaller, lighter, and as noted does not use neutral particles for heating. It is lighter because the protective shield around the machine is considerably thinner than in a Tokamak, decreased from 1-2 meters to several centimeters, reducing the weight of the rocket. It is cheaper to produce, and it can be easily scaled up by lengthening the enclosing cylinder. It is simpler in design than the Tokamaks, making it more reliable. The current plan is to mount 5 of these engines on one rocket, so if one or even two fail the others can safely return the astronauts to earth.

The PFRC is potentially more powerful than alternative machines, so trips in outer space are faster. A trip from the Earth to Mars and back would be less than half the time compared to the alternative engines. This decreases astronaut exposure to natural radiation from outer space, which is itself harmful. Because it runs hotter than Tokamaks, the RFC can use as fuel, the deuterium isotope of hydrogen (whose nucleus has one proton and one neutron, compared to most hydrogen which has only the proton), plus helium-3 (whose nucleus has two protons and one neutron), rather than just deuterium. Much less neutron flow results from the reaction, making it safer for the astronauts.

Status of Development of the Princeton FRC Rocket Engine

The temperature goal for the current PFRC-2 is 500 eV, which is 5.8 million degrees Kelvin. The current rotating magnetic field power is 300 kW, with the plan to go to 500 kW in PFRC-4. The electron density is 10 trillion particles per cc, with a goal of 60 trillion per cc in the PFRC-4. The time of stable activity is 300

1. LaRouche, L. "The Science of the Human Mind, a Treatise on Fundamentals," *Campaigner*, Special Supplement, 1984, February, pp. 2-26.

milliseconds, with the goal of 100 seconds in PFRC-4. Princeton estimates that the full development of the machine will take 4-5 more years.

The machine has been a major focus of the United States government agencies involved. Princeton Satellite Systems (PSS), a research and development company in the aerospace and energy sectors, received funding from the Advanced Research Projects Agency (ARPA) in 2018, $1.25 million in 2019, and $700,000 from 2020 to 2022, but the ARPA funding ended in 2022 and was not renewed in 2023. However, in 2024 the DOE (U.S. Department of Energy) awarded PSS $910,000 for Plasma Heating and Control.

In July 2023, PSS signed an agreement with the British company Pulsar Fusion to share data regarding a fusion rocket engine. Pulsar has stated that it plans to build the equivalent of a functional PFRC-4 by 2027. Pulsar is using the Princeton PFRC-2 cross section image in its advertising, calling it Pulsar.

It is also noted that Princeton Plasma Physics Laboratory (PPPL), a U.S. Department of Energy national laboratory managed by Princeton University, is collaborating with Princeton Satellite Systems on a number of projects. The director of PPPL since 2018 is plasma physicist Stephen Cowley, a British national who was previously CEO of the UK Atomic Energy Authority, a UK government organization responsible for developing fusion energy.

Pulsar has announced that the UK Space Agency is funding a partnership between Pulsar and the University of Michigan to research rocket thrust.

Summary Implications of this Series

Vortex filaments and vortex rings are examples of spontaneous creation of orderly plasma structures. This may have implications for the development of galaxies and solar systems, which show that the universe is moving toward higher and more advanced states, rather than running down. We know that this must be the case from the history of life on Earth; that life, over geological ages, has arisen from non-life, and that intelligent life in the human species has arisen by evolution from other species. The highest form of this intelligent life is creativity, whether used for art, music, science, human relations, or creating nations.

Thus, what we are discussing appears to be representative of the underlying tendency of the universe. Our study of spontaneous generation of complex structures in plasmas may be helpful to understand how this evolution to higher states can occur, which we can term negative entropy, or negative randomness.

A model of this process is in the back-and-forth relation between magnetic fields and currents in plasmas, repeatedly seen in the Princeton Field-Reversed Configuration. This is reminiscent of the back-and-forth process in the counterpoint of Bach and Beethoven.

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