# III. Fusion Primer—Part Two

# The Principles of an Experimental Fusion Energy Device: A Plasma Focus

by Dr. Ned Rosinsky

*This is the second part of a three-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. Reading Part I is recommended to introduce the current Part II.*

## Introduction to Part II

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. This is a loss of approximately 0.7% of the starting mass for most types of fusion. 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.

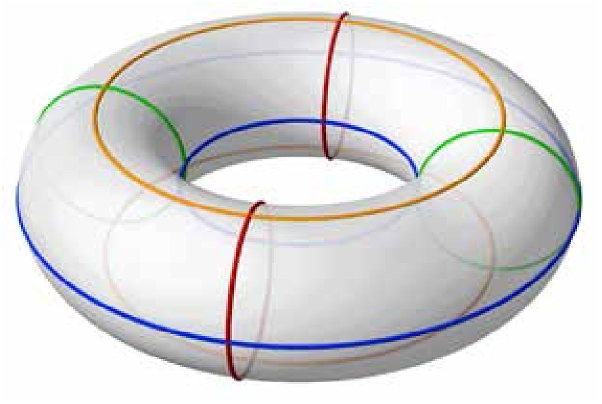
There are a wide variety of magnetic bottles. We will review one type in this article, called a vortex filament. I chose this to review because it demonstrates many of the basic physical principles involved in a relatively simple experimental machine. The knowledge gained from studying the vortex filament can then be used to understand more complex experimental devices currently under development, such as the fusion device that will be discussed in Part III of this article, the Princeton Field-Reversed Configuration.

## Vortex Filaments and Fusion Energy

One of the main problems in keeping a plasma stable, as it is heated and confined in magnetic bottles, is turbulence. Plasma turbulence usually involves uncontrolled rotations and erratic flow patterns. Plasmas, consisting of independently moving and oppositely charged ions and electrons, can become turbulent if they flow around a solid barrier, or even if two flows move around each other. Controlling turbulence has proven difficult.

This may result in the hot plasma not remaining well contained in magnetic bottles, causing the plasma to leave the magnetic bottle and contact the container walls, which may vaporize some materials in the walls. These wall materials can combine with the plasma, leading to more erratic plasma behaviors and energy loss, decreasing the possibility of fusion.

FIGURE 1
**The Torus**



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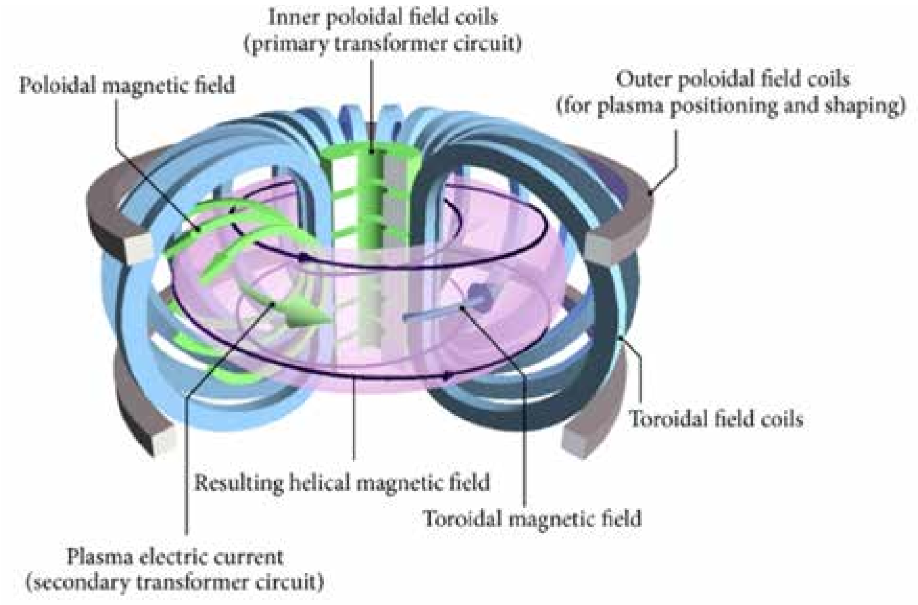
*The torus is a donut-shaped surface. The volume inside it is called a toroid, one way a "magnetic bottle" confines a plasma. Here, circles are drawn on the surface of the donut. A torus has two main directions of movement on its surface, toroidal and poloidal. The blue circles are in the toroidal direction, the long way around. The small red and green circles are in the poloidal direction, the short way around.*

FIGURE 2
**A Tokamak Experimental Fusion Machine**




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

*A tokamak has a toroidal chamber that encloses the plasma, shown in this cutaway view. This chamber is surrounded by magnets, which supply both the toroidal field (in blue) and the poloidal field (in green), to contain the plasma, and to keep the plasma away from contact with the walls. The magnetic fields also cause the plasma to rotate around the toroidal chamber in a spiral. The plasma is usually heated by beams of high-energy neutral particles. Thus far, tokamaks have not yet reached fusion "breakeven." (Source: S. Li, H. Jiang, Z. Ren, and C. Xu, "Optimal Tracking for a Divergent-Type Parabolic PDE System in Current Profile Control," Abstract and Applied Analysis. doi:10.1155/2014/940965*

The major solid confinement container used has been the tokamak, which is shaped like a cylinder that is curved around and connected at both ends like a doughnut, to prevent the escape of the plasma as it is heated. This doughnut shape is termed a toroid. The term "torus" refers to its outer surface (**Figure 1**).

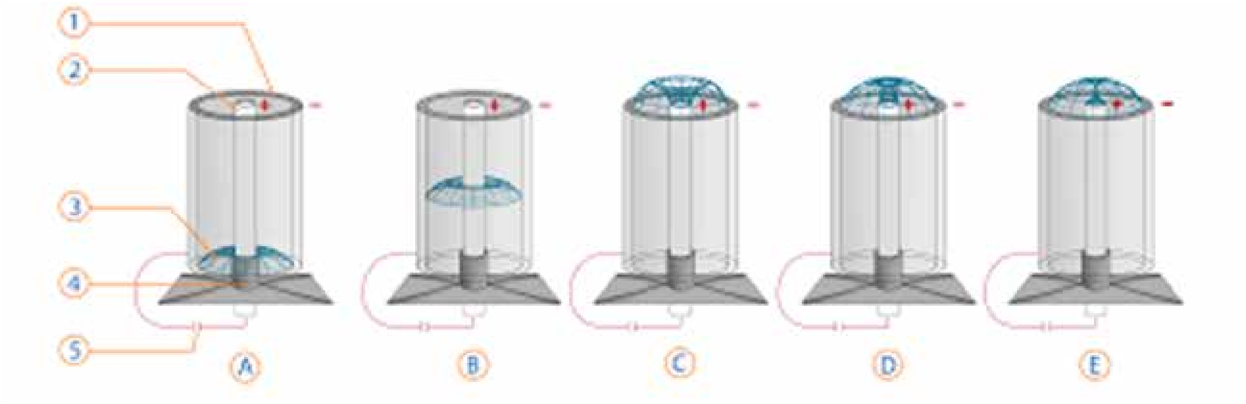
The plasma in a tokamak is contained within the curved cylinder by a variety of poloidal and toroidal wire coils around the outside, creating toroidal and poloidal magnetic fields within the torus (**Figure 2**). The plasma current follows these magnetic field lines and circulates around within this toroid, which keeps it away from the walls. A major problem with this configuration is that when the plasma circulates around inside the toroid, the plasma near the outer part of the doughnut has a longer pathway to circulate around the doughnut, than the plasma near the doughnut hole, and this difference of path length causes unevenness in the plasma flow, resulting in turbulence.

In 1959, Winston Bostick, a plasma physicist who had worked at Lawrence Livermore National Laboratory and other government labs, tried to produce fusion using sparks of electricity within a chamber containing deuterium gas. The chamber contained a straight, narrow metal cylinder, within a wider metal cylinder with the same axis and length, without the cylinders touching each other. The cylinders were connected to a source of strong electrical current, a capacitor bank; and so, the cylinders became oppositely charged: the inner cylinder negative, and the outer cylinder positive. Bostick termed this setup a *Plasma Focus* device (**Figure 3a**). In this view the cylinders appear oriented vertically, and the sequence of steps of formation of the current sheath goes from left to right.

A cross-section of the Plasma Focus—with the cylinders now shown in horizontal, rather than vertical position—is **Figure 3b**. The hatched outlines

Figure 3a

**A Plasma Focus Machine, Showing 5 Stages of Activity**




CC/Karta24

*The Plasma Focus consists of an outer cylinder and an inner cylinder. The cylinders are in a chamber, not shown, that contains a plasma. The cylinders are connected to a capacitor bank so that one is positively charged and the other is negatively charged. The charge produces a large electrical spark between the cylinders in the shape of a ring, or sheath of electric current, between them. This sheath of current moves up the cylinder to the top (from A to C), and then billows out like an umbrella (D), called a halo formation. The halo then collapses onto the end of the inner cylinder (E), creating an extremely hot and dense region, where it is expected that fusion may occur.*

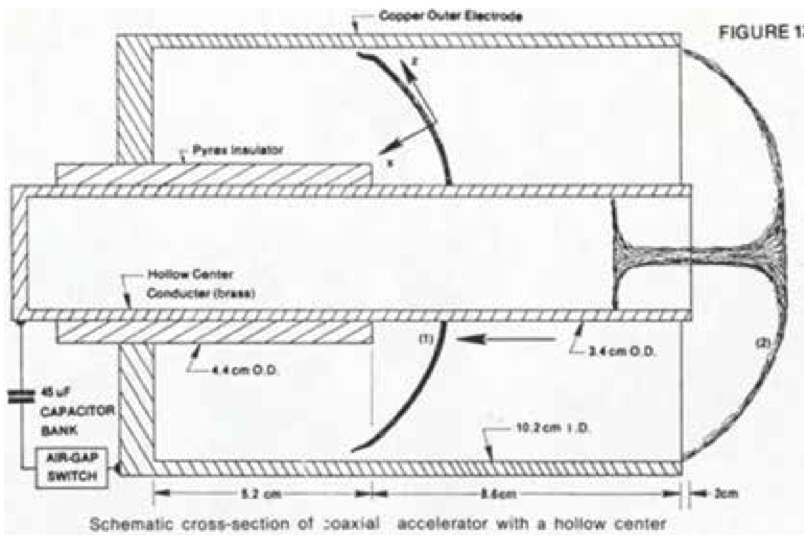
show the inner cylinder ("the hollow center conductor") surrounded by the outer cylinder ("the copper outer electrode"), with the current sheath being accelerated "up" the outer cylinder (moving to the right). A portion of the inner cylinder is insulated from the outer cylinder. The source of current, a capacitor bank, is at the left lower corner.

When the current is activated, a ring-shaped sheath of electric current forms between the cylinders, indicated by the curved lines in the middle of the figure. This current creates a magnetic field, which accelerates the sheath—from left to right in **Figure 3b**, but from the bottom up in **Figure 3a**. At the end of the cylinders the sheath billows out into a "halo"—as shown in both figures—and then collapses into the inner cylinder (creating a pulse of very high heat).

A photograph of the halo formation of the sheath from the oblique view is shown in **Figure 3c**, showing the sheath flowing from inside the hollow center conductor to the outside cylinder. The end view is shown in **Figure 3d**, where the hollow center conductor has been replaced by a

Figure 3b

**Cross Section of a Plasma Focus Machine**

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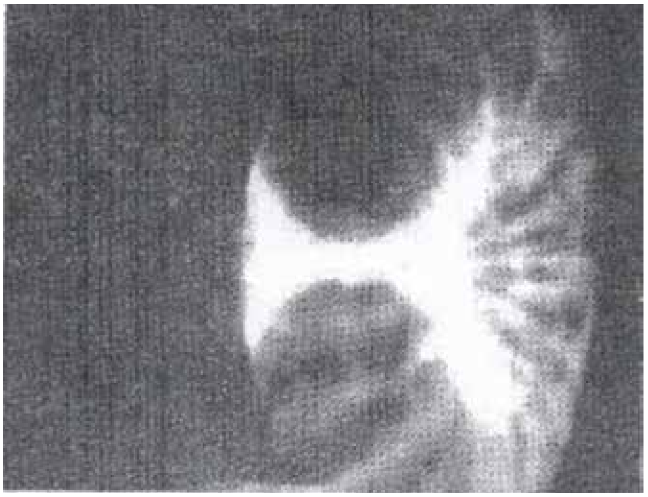
*Fusion pioneer Winston Bostick's diagram of a Plasma Focus, which he developed, shows the cylinders pointed sideways, compared to Figure 3a, where they are vertical. The positive end of the capacitor bank is connected to the outer cylinder, and the negative end to the inner cylinder. When the current was activated, a current sheath formed between the cylinders, shown as two dark arcs, and accelerated "up" the cylinders (here, toward the right). At the end of the cylinders it billowed out like an umbrella or "halo," shown in the cross section as the rounded area on the right, and then folded into the inner cylinder, as shown. This sheath contains intense electrical flow, and this is where vortex filaments form. (Source: Bostick, W., "The Pinch Effect Revisited,"* International Journal of Fusion Energy*, Vol. 1, No. 1, March 1977, p. 30, Fig. 13.)*

Figure 3c
**Photograph of the 'Halo' Formation in a Plasma Focus**



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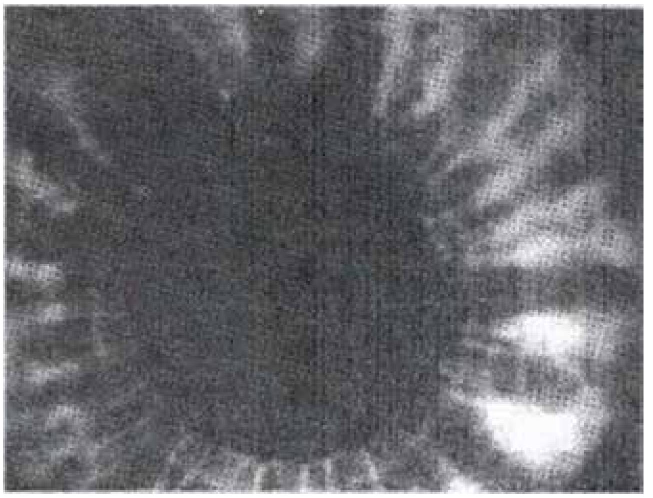
*This photo shows the actual current sheath diagrammed in Figure 3b, billowing out into a "halo." There are streaks of lighter areas, which are streams of intense flows of electrons, and this is where vortex filaments form. (Source: Bostick, W, "The Pinch Effect Revisited,"* International Journal of Fusion Energy*, Vol. 1, No. 1, March 1977, p. 29, Fig. 12b.)*

Figure 3d
**End View of 'Halo' of a Plasma Focus Current Sheath**



*The round dark area in the middle of the photo is the area inside the inner cylinder, which is seen end-on. The streaks of electrons flow from the end of this smaller cylinder out to the end of the larger cylinder. (Source: Bostick, W., "The Pinch Effect Revisited,"* International Journal of Fusion Energy*, Vol. 1, No. 1, March 1977, p. 28, Fig. 11a.)*

solid copper cylinder. The curved dark area at the right of that figure indicates part of the location of the outer cylinder. The current in the sheath is flowing between these two cylinders.

Figure 4
**Corrugated Fiberboard**

Richard Wheeler/Wikimedia Commons

*Winston Bostick described the sheath of current produced by his Plasma Focus as being corrugated; the streaks of strong current, separated by streaks of weak current which are depressed on the current sheath, appeared similar to the surface of corrugated cardboard. He called the strong currents ridges, and the weak currents valleys.*

This view shows that the sheath appears to be formed of large light and dark strips, with the light areas showing the strongest currents. Between these large light strips, there are narrower light strips, which Bostick initially called vortex filaments of plasma. On further examination, he later found that the filaments were not isolated structures within the current sheath, but that "the entire sheath [of current] is really a tissue made up of these vortex filaments."[1] Each filament is less than 1 millimeter wide.

The plasma sheath appears corrugated, like cardboard (**Figure 4**), with the corrugations being the strips of current shown in **Figure 3c-d**.

## Formation and Role of Vortex Filaments in Plasma

Bostick, a fusion pioneer whose Plasma Focus work is still pursued (see below), considered the vortex filament to be a potential magnetic bottle for confining a plasma in a stable state at the high temperatures needed for fusion.

Let us now describe how the individual filaments are formed, in a series of steps (**Figure 5a-g**). This will

1. Winston Bostick, "The Pinch Effect Revisited." *International Journal of Fusion Energy*, March 1977, p. 10.

involve a sequence of currents and magnetic fields, which will be identified with numbers, for clarity. Keep in mind that in an actual filament, these steps are continuous and overlapping. The figures are shown as discrete steps to make the process easier at first to visualize.

We can start with a current, which follows the surface direction of the curving current sheath, and call this Current 1 (**Figure 5a**). This current can create a circling Magnetic Field 1, shown in red in **Figure 5b**. (This was illustrated in Figure 5a of Part I of this series, which was published in *EIR* Vol. 51, No. 33, Aug. 23, 2024, pp. 33-42.)

Magnetic Field 1 recruits a circling Current 2 as shown in **Figure 5c**. (This was illustrated in Part I, Figure 9.) Current 2 can then create a solenoidal field, which produces vertical Magnetic Field 2 in **Figure 5d**. (This was illustrated in Part I, Figure 3b.)

We now have Magnetic Fields 1 and 2 occupying the same space. These fields will add to each other, creating another field, Magnetic Field 3. Think of a boy with a stone on a string twirling the stone around his head, forming a circle, as discussed in Part I. If he bounces up on a trampoline at the same time, the straight upward motion will add to the circular motion, forming an upward spiral. In the case we are considering, the vectors of motion are the upward Magnetic Field 1, and the circular Magnetic Field 2. These will combine to create an upward spiral Magnetic Field 3.

This spiraling of a magnetic field is different from the spiraling of ionized, positively or negatively charged particles around a particular magnetic field line which has "grabbed" the particles. That was shown in Figures 9 and 10 in Part I. Here, we have magnetic field lines with particles spiraling around them, and these magnetic field lines are themselves spiraling around the developing vortex filament. To visualize it, imagine that the particles moving around a magnetic field line move in a narrow spiral around it, while its field line rotates around the filament in a much wider spiral.

Magnetic Field 3 can then recruit ionized plasma particles to make an upward spiraling current, designated as Current 3 (**Figure 5e**). This current will spiral upward because there is an electrical field between the cylinders which has created the spark sheath, and this same electrical field pushes the current that is cycling around the magnetic field line to move in the upward direction.

The spiral Current 3 will then form a solenoid, creating a magnetic field pointing up in its center area, and then looping down further away from the center. For clarity, we've called them Inner Magnetic Field 4 going up and Outer Magnetic Field 4 going down, though these two fields are part of the same field (**Figure 5f**). Inner Magnetic Field 4, pointing upwards, will add to Magnetic Field 3 in the central portion of the filament, causing the spiral there to elongate (increase its pitch), resulting in what we call Magnetic Field 5. The returning weaker, downward Outer Magnetic Field 4 will combine with the upward Magnetic Field 3 in the peripheral part of the filament, decreasing the pitch of the field and thus creating a spiral field called Magnetic Field 6 (**Figure 5g**).

Think again of the boy whirling the stone on a string, while jumping on a trampoline. If he jumps upward faster, the resulting spiral will be stretched out in the upward direction, which is described as increasing the "pitch" of the spiral. If he jumps up more slowly, the resulting upward spiral will be more compressed—its pitch will decrease. Pitch is the length of spiral that is required to make a complete 360-degree turn around the axis.

The resulting Magnetic Fields 5 and 6 will recruit particles of ionized plasma to create currents parallel to these two fields, designated as Currents 4 and 5.

The steps in Figures **5e-g** can be reiterated, with each repetition resulting in a more nearly vertical current flow near the axis, and a less vertical flow in the outer areas, until the vortex filament is completed.

The total effect of this entire series of developments is that the completed vortex filament has a vertical core magnetic field and vertical current, and the rest of the filament is spirals. These spirals are stretched out long (greater pitch) near the central axis, and shorter (smaller pitch) further away from the axis.

The currents are everywhere parallel or nearly parallel to the magnetic field lines, and this is important for the stability of the plasma.

## 'Dialogue' of Currents and Magnetic Fields

We have presented the development of the vortex filament as a series of steps. In the actual plasma, however, each of the steps is small and they are nearly continuous. The end result is that the spiral pitch of the currents and fields increases continuously as one proceeds from the outside toward the central axis of the filament.

For example, Current 1 starts immediately when the current sheath is set up and the initial corrugations in the sheath exist. It immediately begins to create Magnetic Field 1, as a straight-line current in a wire creates a magnetic field in a cylinder around the wire—this was illustrated in Part I, Figure 5. As soon as Magnetic Field 1 starts, it begins to recruit particles into Current 2, and so on. Thus, the steps outlined above as numbered, sequential fields and currents, are actually both overlapping and continuous, with the main driving force being the initial current in the plasma sheath.

Looking at the overall pattern of development of the vortex filament, one can see something similar to the statement we quoted about the "dialogue" in Einstein's General Relativity, in which "mass tells space-time how to curve, and curved space-time tells mass how to move." In the case of the vortex filament, currents tell magnetic fields how to curve, and curved magnetic fields, by grabbing charged particles, tell currents how to move.

Also, note that plasmas, in general, are not quiet states of matter. There are usually currents, flows, and turbulence present across the plasma, even if at a low intensity. Thus, what I am describing above is a general tendency for these orderly structures to occur despite irregularities in the plasma. For example, the sudden occurrence of a current sheath in a plasma, which Bostick used to initiate the development of the filament, would itself be expected to cause a disturbance in the plasma flow.

In 1974, Bostick started a long-term collaboration with Lyndon LaRouche. When LaRouche started the Fusion Energy Foundation (FEF) in 1974, Bostick became a member of its Scientific Advisory Board. In 1977 the FEF started the *International Journal of Fusion Energy* (*IJFE*), and Bostick was on the Initiating Editorial Board. During the late 1970s and 1980s Bostick participated in numerous scientific seminars convened by LaRouche.

In these discussions of his experimental work, Bostick indicated that small differences of pitch, between the nearly-parallel spiral flows of electric current and magnetic field, would cause small forces to act on the flows and push them toward the central axis of the vortex filament. Thus, the spontaneous formation of these vortex filaments was not quite to be termed "force-free"; LaRouche called it "least action."

The term "least action" refers to a notion created by the great German physicist and philosopher Gottfried Wilhelm Leibniz (1646-1716) as greatest efficiency of action—the least action required to perform the relatively greatest amount of work. The circle, for example, is the shortest line which bounds the maximum area within it. In human terms, action performed by people can become more efficient as technology develops, such as mechanized agriculture, or using a steam engine for power.

In a vortex filament, current can flow more freely, more efficiently, if the lines of flow are parallel to magnetic fields, *because the current is not crossing magnetic field lines, so the current is not disturbed by the field*.

## Filaments in Plasma and in Nature

Having found that a plasma may create this complex structure from simple initial conditions, Winston Bostick investigated how to *control* plasmas by understanding the spontaneous rotational flows, and then using them to confine plasmas at high temperatures, so that they could fuse and produce fusion energy.

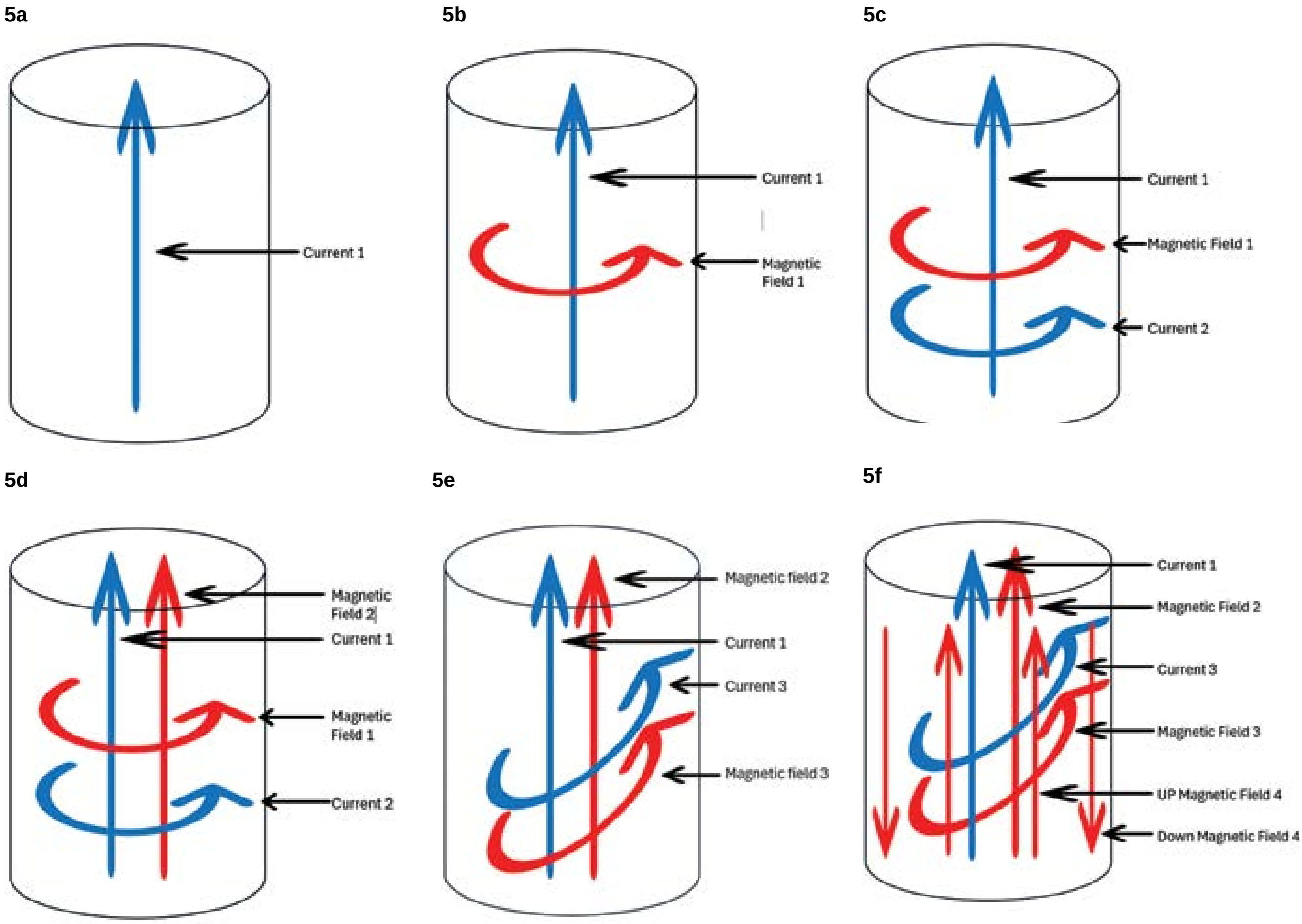
Where do we find filaments in nature? Lightning is a giant plasma spark, and it may support this kind of filament development. There may also be numerous visible filaments around the main lightning spike in the damp area of a storm. There are very large electron currents and magnetic fields that emanate from the sun, and there is evidence that vortex filaments may form in solar flares. There are gigantic magnetic fields and currents that emanate from supernovae—exploding stars—which may create these structures. In a related development involving magnetic fields, the arms of some spiral galaxies have recently been found to have long-range magnetic fields, with the direction of the fields alternating from one arm to the next, indicating some kind of long-range, coherent electromagnetic action across a galaxy.

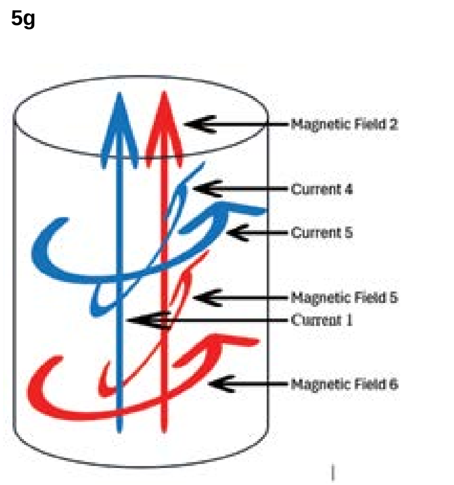
Bostick referred to evidence that vortex filaments in fusion machines occur not only in response to high energy current flows such as current sheaths, but can be found throughout the plasmas in these experimental devices. Going back to the steps of the vortex formation in **Figure 5a-g**, it is evident that the initiating event could be any straight or curved line of current in a plasma.

Because the currents in vortex filaments follow magnetic field lines, the currents are not disturbed by the magnetic fields, and the filaments conduct currents very efficiently. Bostick generalized the formation of vortex filaments in the Plasma Focus device, to be a process that can occur throughout the plasma. He wrote in the *International Journal of Fusion Energy* in 1977 that—

> "equilibrium plasmas" are more a theoretical

Figures 5a-g
**Stages of Development of the Vortex Filament**




Dr. Ned Rosinsky/EIR

*Progression of diagrams is carefully explained in the article text. The electric currents are indicated in blue, the magnetic fields in red.*

convenience than a reality, and … real plasmas are experiencing rising magnetic fields and accelerations; the plasmas will contrive to form local vortex filaments everywhere so that they can carry their current always parallel to a local magnetic field.

These vortex filaments come in all sizes: large ones, like arteries, small ones, like capillaries; in their totality, they provide the vascular structure for carrying the electric current that the plasma carries. The plasma so constructed, however, is a "hemophiliac": a sudden shock or overstress at one point can crush the capillaries and cause bleeding. Thus, the local current-conducting paths of small vortex filaments are destroyed … and the resistance to currents increases suddenly.[2]

This sudden increase in electrical resistance was surprising to most physicists, and it was the main reason that Bostick concluded that vortex filaments occur throughout plasmas.

## Continuing the Plasma Focus

Winston Bostick's attempt to use these rotating filaments for plasma containment, set him at odds with many fusion energy researchers, who were trying to produce the conditions for fusion by decreasing turbulence in their machines. Bostick found evidence of high-energy neutrons emitted from vortex filaments, indicating that fusion reactions were occurring within them.[3] However, he died in 1991 before he could reach breakeven in his experimental machines.

Bostick's line of research using the Plasma Focus was subsequently taken up at ten research locations in eight nations, including Argentina, Chile, Poland, Malaysia and Singapore. In 2001, a decade after Bostick's death, Eric Lerner, a former colleague of Bostick at the Fusion Energy Foundation, started an experimental fusion machine based on the Plasma Focus, called the Dense Plasma Focus, in an independent company called Lawrenceville Plasma Physics (LPP) in New Jersey.[4] Lerner's team has continued to develop this machine up to the present time, and currently holds the world record for plasma temperature, in the range of 2.4 billion degrees K.

This Dense Plasma Focus (DPF) device is planned to use proton–boron-11 fuel, which does not produce neutrons, and is therefore safer than other fuels. Protons and boron-11 are plentiful and cheap to isolate. So far, the DPF experiments have not actually used proton–boron-11 fuel. But the 2.4 billion K temperature which LPP has already achieved, is above the 1.5 billion K threshold for proton–boron-11 fusion reactions, which would run best at 6 billion degrees K. Lerner and his team believe this machine could be easily scaled from table-top to moderately large.

The DPF uses a central, straight, negatively-charged cylinder, surrounded by eight straight, nearly parallel positive rods arranged in cylindrical formation. The central cylinder is connected to the negative terminal of a capacitor bank, and the positive rods are connected to the positive terminal. This apparatus is built into a vessel that can contain a plasma. When the current is turned on, a rapid flow of electrons runs through the negative inner cylinder, and then forms a spark sheath with the outer positive rods. A separate solenoidal field that surrounds the rods then drives the current sheath down the rods to the rod ends and the sheath billows out like an umbrella. The sheath then very quickly collapses onto the end of the inner cylinder, which causes immense, sudden heating of plasma at the cylinder end.

The Lawrenceville Plasma Physics website features an "Evaluation of LPPFusion Dense Plasma Focus Research" by a group of leading plasma physics experts, dated 2021. According to the website:

> The committee, chaired by Dr. Robert L. Hirsch, former director of fusion research for the United States government's Atomic Energy Commission and Energy Research and Development Administration, concluded that "LPPFusion has made an impressive effort to address DPF physics and engineering issues given the limited number of personnel involved," but that the "program is vastly underfunded and merits a much higher funding level."

Thus far the program has raised approximately $10 million from government grants and investors.

We are all mortal, but good ideas that we create may live beyond our own lifetimes, and may have the potential for helping humanity far into the future. LaRouche has addressed this point regarding human culture in general, whether it takes the form of science, art, economics, or statecraft, as the "Simultaneity of Eternity."[5] We live, in the best of cases, to benefit future generations. This continuation of Bostick's work is therefore important beyond the details of a specific area of science.

As noted at the start of this part, the final, Part III of this series can use the knowledge gained from studying the vortex filament, to understand more complex experimental devices currently under development. Part III will discuss as a particular example, the Princeton Field-Reversed Configuration.

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2. Winston Bostick, ibid., p 21.
3. Winston Bostick, ibid., p 34.
4. https://lppfusion.com
5. Lyndon LaRouche, "How Youth Can Uplift the 'Failed Generation'," ***Executive*** *Intelligence Review*, Vol. 31, No. 37, Sept. 24, 2004, pp 25-35.