The pinch effect revisited

What appeared to some fusion researchers as "instabilities," turned out to be self-organizing plasma vortex filaments. Part 2 of a series.

In Stockholm, September 1956, at a conference on Electromagnetic Phenomena in Cosmical Physics at a special Saturday morning session following the scheduled conference, Igor Golovin gave a description of the Soviet Ogra program and Lev Artsimovitch gave an analysis of the instabilities of a pinch with an applied axial magnetic field. The U.S. Atomic Energy Commission (AEC) was still keeping most of its CTR program under security wraps.

The author remembers having a conversation in 1956 with a very highly placed physicist employed in the U.S. CTR program at one of the large U.S. national laboratories. The author opened the conversation by advocating that all security classifications on the U.S. CTR be dropped. The highly placed physicist responded by saying that he agreed that the classification should be dropped "but we should wait for six months until we have some more results." Such a research-inhibiting attitude was undoubtedly born of a professional life lived too long under the protection of security classification. In 1956 at least the United Kingdom and the U.S.A. agreed to exchange information.

The forthcoming International Atomic Energy Agency (IAEA) Atoms for Peace Conference in 1958 at Geneva was the occasion for Lewis Strauss [then head of the U.S. Atomic Energy Commission] to finally declassify the U.S. CTR effort. Strauss wanted a first class show of U.S. experimental equipment at the Geneva exhibit hall, so most of the U.S. experimenters spent months polishing, shipping, and setting up the U.S. equipment for the exhibit. One Princeton experimenter estimated that the U.S. experimental program was set back nine months, at least, by the show. But then the Soviets must also have been set back. It is a pity such a vast effort at a show was spent on the small town of Geneva. If the show had been a road show held in New York, London, Paris and Moscow, many more people would have seen it. But apparently the show was not for the people of the world: It was for the U.S. AEC and United Kingdom to impress the Soviet physicists and for the Kurchatov Institute of Atomic Energy to impress the U.S. and United Kingdom physicists.

Considerable research on efforts at stabilization with the use of B_z in linear and circular pinches was reported at the IAEA Geneva conference in 1958. The results added up to a somewhat discouraging outlook for the pinch effect as a fusion device. In order for the magnetic field configuration to maintain stability the electrical conductivity of the plasma should be high and remain high so that the B_z inside the pinched plasma column should not be permitted to diffuse and mix rapidly with the B_θ outside the column. The appearance of increased B_z outside the pinched column resulted in $m=1$ instability for long wavelengths, and the deterioration of sharply defined magnetic field distributions into "diffuse" volume distributions was definitely harmful to stability. Also, the electrical conductivity of the plasma remained disappointingly low.

The electrical skin depth in the plasma is a good measure of the diffusion distance as a function of time. If finite thermal conductivity is allowed for, but radiation losses are neglected, it is predicted theoretically that the mean plasma temperature over a skin depth in from the pinch surface is about

$$T_r = \tfrac{1}{3}T_c = \frac{H^2}{24\pi nk}$$

where H is the magnetic field amplitude and n is the particle density in the undisturbed region of the pinch. T_c is the maximum temperature compatible with pressure balance at density n. The classical theory of conduction of electricity in an ionized gas states that the electrical conductivity varies as $T_e^{3/2}$ where T_e is the electron temperature.

As the H_z and H_θ fields (or the B_z and B_θ) interdiffuse, the stability of the pinch diminishes. On the same time scale on which the stability is lost the pinch is heated. In making a practical thermonuclear machine of the pinch type one must therefore arrange for the plasma to gain energy fast enough to overcome radiation losses, but not so fast as to destroy pinch stability in times insufficient for appreciable fusion to occur.

The experimental results in both linear pinches and toroidal pinches (where heat conduction to the electrodes can be eliminated) are that the plasma electrical conductivity is distressingly low. This result occurs in discharges where, from the point of view of expected energy balance in the transfer of magnetic energy to the plasma from the calculated $T_r = \tfrac{1}{3}T_c$, one would expect the electrical conductivity of the plasma to be high: For example in cases where one would calculate that T_c should be about 3,000 electron volts (ev), the electron temperature calculated from electrical conductivity measurements was $T_e \cong 10$ ev. The electrical conductivity can be measured by the rate of diffusion of the H_z and H_θ fields and by the decay time of the shorted pinch current in the machine. The interpretation given at the time of these measurements (1955-58) was that if the plasma was absorbing energy from the magnetic field, it was losing that energy equally rapidly by some process such as accelerated runaway electrons which would encounter the chamber wall.

Colgate, Furth, and Ferguson, in their 1958 paper at the IAEA conference, point out that in their toroidal stabilized pinch the plasma resistivity is 20 to 100 times as great as the highest resistivity which would be tolerable for a thermonuclear reactor, namely the classical resistivity of a 200 ev plasma. Even if ion temperatures of 100 kev could be produced, as long as the electrical resistivity requirement is not met, the containment time will be too short to allow economical operation. Thus they felt that nothing can be done to improve the plasma conductivity, and therefore the main emphasis of stabilized pinch research should at this point belong not to the attainment of high plasma temperatures, but to the understanding of the energy dissipation phenomena in the plasma.

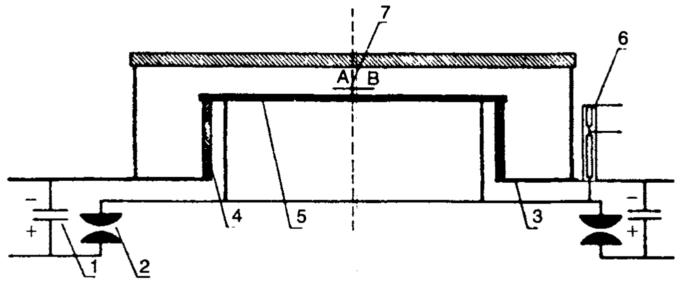
And indeed the concept of turbulent heating as a CTR process has been actively pursued in the U.S.A., United Kingdom and U.S.S.R. as an extension of this work. A high current is passed through a plasma column containing a B_z field and energy is imparted to the plasma by forcing the current through the anomalously high resistivity which the plasma presents to the current; it is this anomalously high resistivity which was making its appearance in the stabilized pinch experiments. Investigators in this field claim that the anomalously high resistivity results from ion-acoustic waves which are excited by an instability which results when the electron drift velocity, under the influence of the applied electric field, exceeds the ion-acoustic velocity. In these turbulent heating experiments the sudden onset of high resistivity is usually accompanied by the emission of X-rays, neutrons (in deuterium), and microwaves, similar to what happens in the ordinary dynamic pinch at the time of pinching.

The United Kingdom's SCEPTRE and later the large toroidal ZETA apparatus at Harwell and Culham were stabilized pinches on a large scale (large diameter, approximately 3 meters for ZETA). (See Figure 5,* *EIR*, Feb. 8, 1991 "The pinch effect revisited," Part 1.) The neutrons which came from SCEPTRE and ZETA (approximately 1958) were shown experimentally to come also from some acceleration process and not from a thermalized deuteron plasma. ZETA also showed anomalously high resistivity which must have been associated with the same type of turbulence that occurs in the turbulence heating experiments and in the stabilized pinch experiments. ZETA exhibited internal structures that had some of the properties of plasma vortex filaments.

It was gradually conceded that this effort (1952-63) to develop a CTR magnetic containment device out of the pinch effect failed to reach its objective. This effort involved some of the best experimentalists and theoreticians in the U.S.A., U.S.S.R., United Kingdom, France, and Sweden.

FIGURE 6

Schematic diagram of the Filippov electrode geometry which produced 10^{10} neutrons in 1961.



1) capacitor power supply, C=180 microfarad
2) ring vacuum discharger
3) cathode
4) porcelain insulator
5) inner electrode (anode, diameter=480mm)
6) voltage divider
7) cross-shaped slit (A and B)

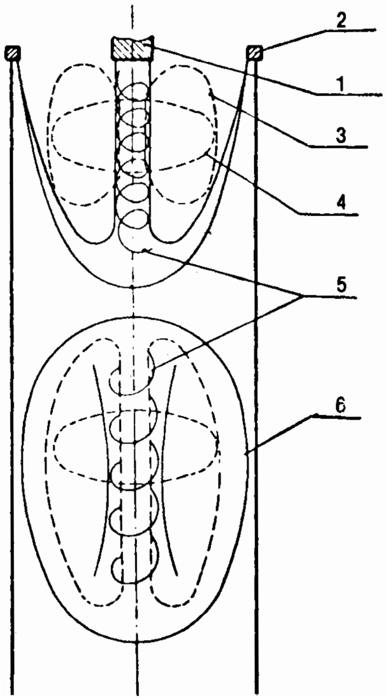
The leaders of the CTR programs in the various countries eventually decided that a self-pinched plasma column had no future as a CTR magnetic-containment reactor, and financial support for pinch-effect research came to be drastically curtailed and in some cases eliminated. On the other hand, the Tokamak concept that now dominates CTR planning is a kind of B_z stabilized pinch (like SCEPTRE and ZETA) where the B_θ is small compared with the stabilizing B_z (the toroidal current is kept below the "Kruskal limit") and the fields are well mixed.

Although the pinch effect has now completely lost the CTR center stage to the Tokamak, the pinch effect as a complex physical process that can come up with surprises for the experimenter has been by no means dead!

The next important announcements on pinch effect research were made at the IAEA conference on CTR in 1961 in Salzburg. The Soviet group under N. Filippov at the Kurchatov Institute reported results on a pinch produced with the electrode structure shown in **Figure 6.** The conventional pinch effect produced between the two "conventional" electrodes as shown in Figures 2 and 4 [see *EIR*, Feb. 8] (and in Columbus I and II) can produce a maximum of about 10^4 neturons per pulse with a filling of about 100 microns of deuterium. The Filippov-geometry pinch operating in deuterium at a pressure of a few Torr produced about 10^{10} neutrons

FIGURE 7

Diagram of circulation cells produced by Komelkov's fountain pinch.



Structure of the currents and magnetic fields in a plasma jet and plasmoid.
1) central electrode
2) ring electrode
3) longitudinal field
4) azimuthal field
5) internal current helix
6) plasmoid
These circulation cells were believed to be force-free configurations.

per pulse!

Kvartskava from Sukhumi in the U.S.S.R. gave a paper that showed, in framing camera pictures, many beautiful examples of striations or filaments which occur in both the conventional Z-pinch and the θ-pinch. For the most part these striations were perpendicular to the impressed magnetic field. At approximately this time Bodin of the United Kingdom reported circular striations in their pinch (observed with a coil made out of metal screen). The striations reported by Bodin were "explained" by Rosenbluth, Furth, and Kileen in terms of the finite-resistivity driven instability in the tearing model. But the citation of this instability was really no complete explanation of the phenomenon. As the work at Stevens was later to demonstrate, these striations of Kvartskava and Bodin are plasma vortex filaments that form in the corrugations which naturally form in the current sheaths of the Z-pinch and θ-pinch.

Also in the early 1960s Komelkov of the Kurchatov Institute produced the "fountain pinch" with a large capacitor bank that rings through many cycles when being discharged between the electrode structure shown in **Figure 7.** He and his colleagues observed that for each half-cycle of current a circulation cell was propagated down the gas tube (shown in Figure 7) and that these circulation cells contained an axial (Z) magnetic field at the axis and a toroidal (θ) magnetic field off the axis. These toroidal circulation cells were large examples of the small (0.1 mm diameter channel) circulation cells to be reported later by the Stevens group.

In 1962 Daniel Wells, working on his thesis at the Princeton Plasma Physics Laboratory, produced plasma vortex rings from a conical θ-pinch gun. These vortices contained both poloidal and toroidal magnetic fields and were later judged by Wells to be examples of collinear flow which were both Lorentz and Magnus force free.

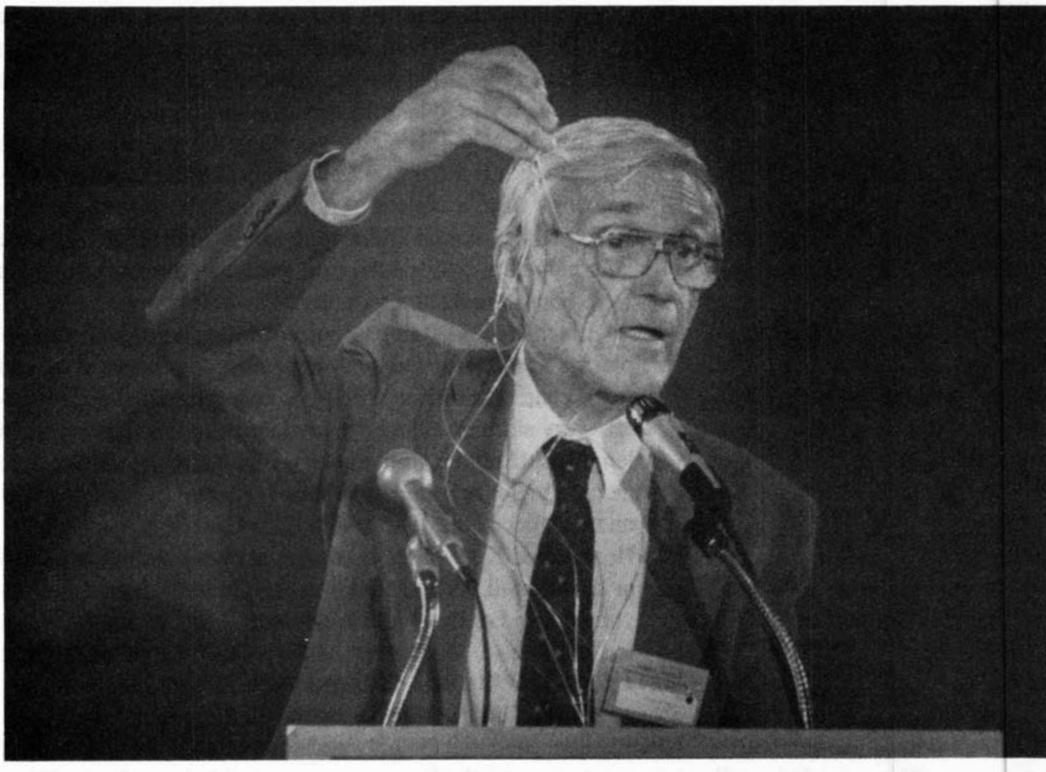
Later at Los Alamos Joseph Mather used the coaxial-plasma-accelerator geometry to produce Z-pinches at the end of the center conductor. This geometry proved to be functionally very similar to the Filippov geometry (though longer in length and smaller in diameter), and he achieved the large neutron yields reported by Filippov. Mather gave a fine paper on this work at the 1965 IAEA CTR Conference at Culham. He reported X-ray pinhole camera photos which showed two or three small X-ray sources along the axis about 1 cm beyond the end of the center conductor.

1964-74: 'Omnis plasma est . . .'

During the 1964-74 period the CTR world at large generally conceded that the holy plasma focus empire was divided into two parts, the Eastern empire presided over by the Filippov group in Moscow and the Western empire presided over by Mather at Los Alamos. However, to indulge in such a general concession would be to ignore the fine work on the heavy-liner pinches and the plasma focus carried on by Linhardt and Maisonnier's group at Frascati; the superb optical diagnostic work by Peacock's group at Culham and the French group at Limeil; the pioneer work on filaments at Sukhumi; the work by Bernstein and others at Aerospace on the neutron energy spectrum and the neutron collimation work which showed the motion of the location of the neutron source along the axis; the work by J.H. Lee at Langley on the neutron energy spectrum by time of flight and on the X-ray energy spectrum; the work of Potter in computing the history of the current sheath during collapse; the work of Beckner on X-rays from the plasma focus; and the work by Luce and others at Aerojet Nucleonics in attaining large neutron yields. The fine observational work on the pinch effect carried out with a Kerr cell by Curzon and others at Imperial College should also be cited.

Mather gave the one-hour invited paper on the plasma focus at one of the plenary sessions of the American Physical Society Plasma Physics Division Meeting in Madison, Wisconsin in November 1971. Mather was invited to write the section on the plasma focus in *Methods of Experimental Physics*. At the IAEA meeting in Novosibirsk in 1968, Mather was the honored guest at a dinner party attended by most of the Soviet workers in the plasma focus field.

Mather developed the "unpinch" glass insulator which proves to be a *sine qua non* for all properly operating plasma



Stuart Lewis

The late Dr. Winston Bostick speaking at a November 1984 conference of the Schiller Institute.

focus machines: With Mather's insulator the current sheath break loose from the insulator and proceeds down to the annular space between the electrodes.

Mather was one of the first to apply an initial axial magnetic field (B_z) to the plasma focus and he obtained some interesting X-ray pinhole photos of the resulting plasma column. However, in his diagnostic work Mather did not use sufficiently small pinholes to measure the true size of the small plasma concentrations that produced the X-rays. Also the X-rays coming from the copper vapor from the solid center electrode obscured some of the images from the deuterium plasma. Thus Mather did not realize the full potentialities of the X-ray pinhole photo technique. Mather's group also used image converter photography, but they did not observe the filamentary structure reported later by Nardi, Prior, and Bostick, who showed that shadowgraph and Schlieren photography can pick up the filamentary structure even when the image converter photos are incapable of resolving the filaments. Nardi, Prior, and Bostick thus maintain that the filamentary structure is always there in the current sheath even if the photographic efforts of a particular observer fail to reveal the filaments.

The author assumed the duties of head of the Physics Department at Stevens Institute of Technology in 1956 and was able to do very little effective experimental work until 1961-62 when he went to France and England on a National Science Foundation Senior Postdoctoral Fellowship. At Fontenay aux Roses in 1962, he studied diamagnetic vortices in plasmas projected across a magnetic field by a small plasma gun. This was an extension of work he started at Lawrence Livermore Laboratory in 1954. In 1962-64 at Stevens these diamagnetic vortices were studied extensively by probes in the plasma coaxial accelerator by Farber, Prior and Bostick. In 1964 image-converter photos taken at Stevens by Grunberger and Prior showed that similar diamagnetic vortices were produced in *pairs*. These photos were obtained by projecting plasma from several types of plasma guns at a small "magnetosphere" produced by a pulsed current in a loop coil. The plasma was projected primarily in the equatorial plane and photographed from one of the poles. The properties of these diamagnetic vortices in the model magnetosphere were also investigated with probes: the electric field, given by $\vec{E} = \vec{v} \times \vec{B}$, can be picked up very easily by a double probe where $\vec{B}$ is the background magnetic field and $\vec{v}$ is the rotational velocity of the plasma mass. These diamagnetic vortices when observed in the plasma coaxial accelerator by Farber and Bostick were found to roll, like rubber bodies, upon each other like gear wheels that mesh. The diamagnetic vortices have their rotational axes lined up parallel to the background magnetic field. In the guiding-center approximation for a diamagnetic vortex rotating in one direction the diamagnetic current is carried by the electrons. For the vortex rotating in the opposite direction the current is carried by the positive ions.

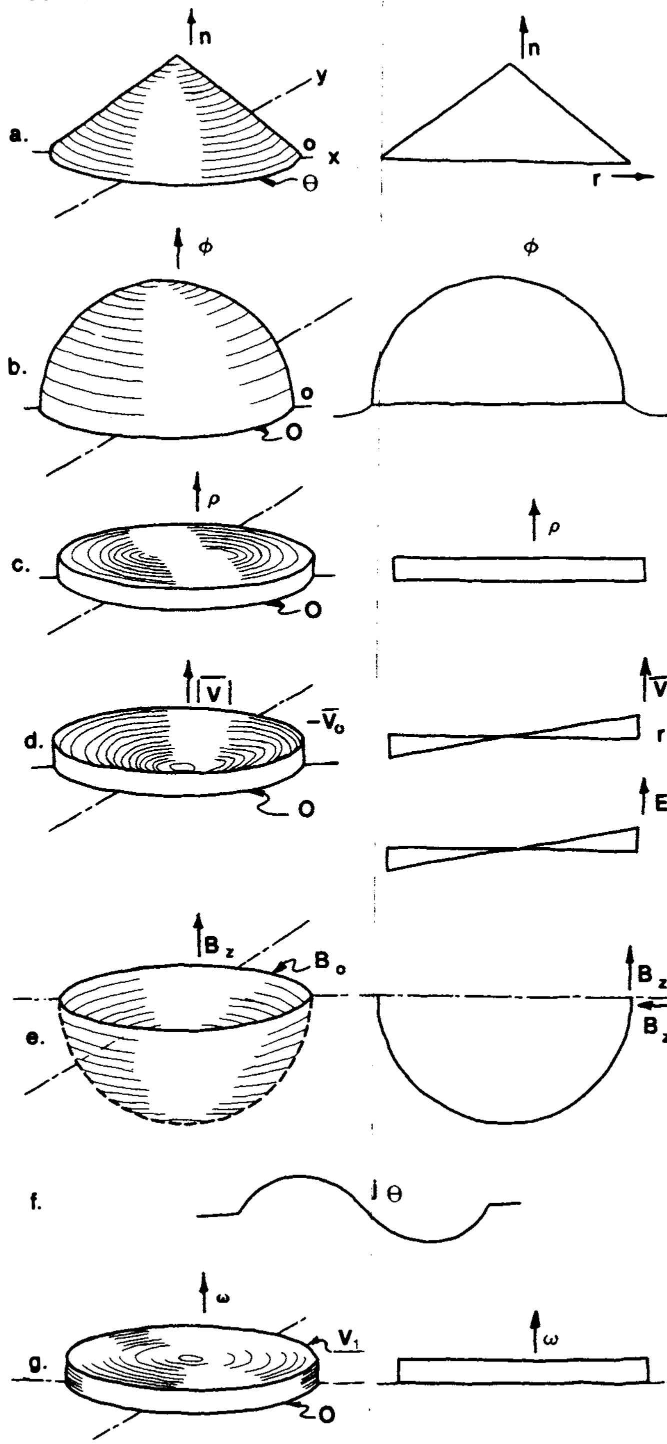
Indeed a pair of diamagnetic vortex filaments walking across a magnetic field is the way in which plasma is lost to the wall in a conventional mirror machine after a flute instability has developed. Poukey was the first to work out theoretically a self-consistent field pattern for such a pair of diamagnetic vortex filaments. In **Figure 8** the profiles of a single diamagnetic vortex filament are diagrammed, and the profiles of a pair are shown in **Figure 9.** These vortices rotate like rigid or rubber bodies. The diamagnetic vortices have been called circulation cells by Yoshikawa and Harries where they have been so identified in experiments at Princeton Plasma Physics Laboratory, and by workers on the multipole machine at Wisconsin.

In experiments by Lovberg in 1963 and Prior, Farber, and Bostick to accelerate plasma in a coaxial electrode geometry, it was noticed that the current sheath broke up into radial striations. Most experimenters in the plasma accelerator and plasma focus field believed that the presence of these striations indicated an inferior current sheath and attempted to get rid of them. In 1965 Prior and Bostick used a hexagonally shaped center conductor and observed, with image-converter photos, that the striations occurred in *pairs* at the flat sides of the hexagon. This occurrence in pairs was a clue that these striations might also be plasma vortex filaments. Subsequent experiments were to prove that the striations were vortex filaments. Bostick, Prior and Farber and Grunberger had already observed the aforementioned production of pairs of diamagnetic vortex filaments where the axis of the vortex filament is lined up along an externally excited background magnetic field. Now these striations in the plasma focus, which were actually paramagnetic plasma vortex filaments whose axis is perpendicular to the background magnetic field, were inadvertently revealing their true identity.

A diagram of the field and flow structure of these paramagnetic vortex filaments is shown in **Figure 10.** It must be recognized that this indicated structure is believed to be Lorentz force-free and Magnus force-free and is drawn as such, similar to the structures reported by Wells and Komelkov. The diameters (<1 mm) have been measured with image converter photography and the local B_z fields with coupling-loop probes. It would be impossible experimentally to map in detail such a field pattern for structures that are so small in diameter. These vortices are large-amplitude, convective Alfven waves that (in the lab system) do not travel away from one another along B_z because they are traveling in a medium that develops a particular flow structure.

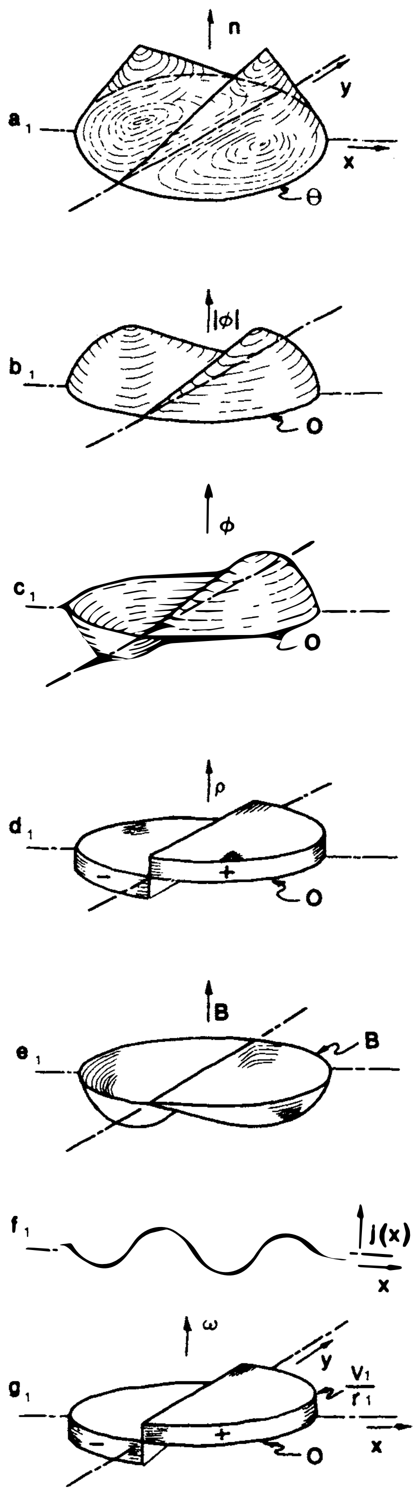
Figure 11 shows 5 nanosecond-exposure-time image converter photos of the paramagnetic vortex filaments (radial) that occur in the small Stevens plasma focus current sheath. The filaments that are concentric to the machine axis and which bridge between the radial filaments are diamagnetic vortex filaments. **Figure 12** shows examples of the current sheath with filaments as it develops in the Stevens plasma focus with both solid and hollow center electrodes. **Figure 13** diagrams the electrode structure of this small (~5 kilojoules) Stevens plasma focus.

FIGURE 8



Profile for a single diamagnetic vortex filament whose rotational axis is lined up along the background magnetic field B_0 in the z direction, n is ion density, ϕ is electrical potential, ρ is charge density, v is local rotational velocity, B_z is local magnetic field which is influenced by the diamagnetic current, E_r is the radial electric field, j_θ is the diamagnetic current density, ω is the vorticity which is also the angular velocity.

FIGURE 9

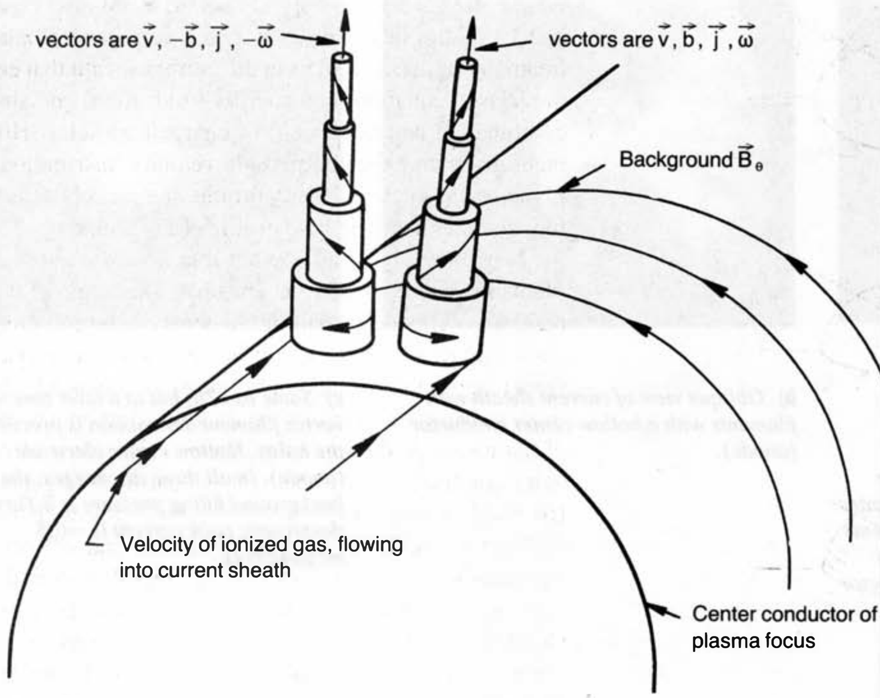


Profile plots for a pair of diamagnetic vortices moving in the y direction across the background magnetic field B_0 which is in the z direction.

Nardi has shown theoretically, from magnetohydrodynamic (MHD) treatment, that if the current sheath of the plasma focus becomes corrugated vorticity can be expected. Figure 11b, which is an image converter profile photo, shows clearly the corrugated current sheath, as do also Figures 11 and 12. Nardi has also developed a very general analytical treatment of these vortices in the current sheath that employs the Vlasov equation with sources (ionization) and sinks (recombination and scattering) of charged particles. His treatment gives an expected particle velocity distribution in the filament, the current density profile, the particle density profile, and the magnetic field profile of the filament.

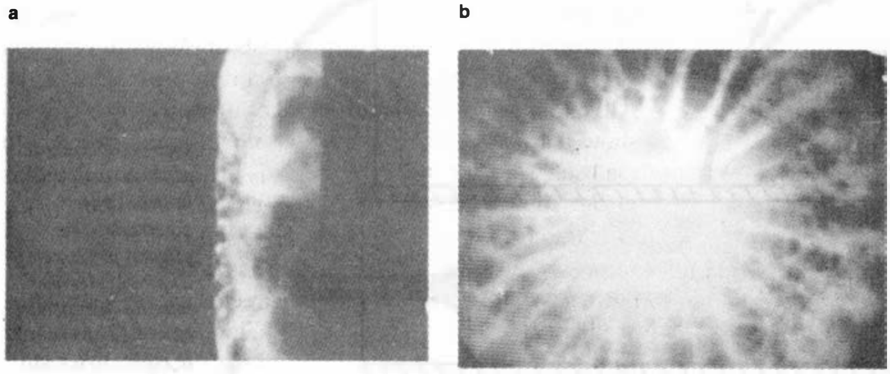
Now one might ask, "What role do these paramagnetic filaments play in the current sheath?" The origin of the magnetic structure of each pair of filaments can be comprehended from Figure 10 where it can be seen that a corrugation in the background magnetic field causes an oppositely directed mass swirling (or vorticity) in the two components of a pair of filaments. At the same time there is mass flow toward the outer conductor. This resultant helical flow (right hand or left hand) along each pair of the filaments will twist the background field lines into the right-hand and left-hand configurations shown in Figure 10. The fact that local B_z fields (i.e. fields parallel and antiparallel to the axes of the filaments) have been generated aids the electrons in carrying currents *along* these local B_z fields. These B_z fields at the filamentary axes functionally play the role analogous to the superconducting niobium-tin fibers embedded in a background of copper in a superconducting coil: The plasma vortex filaments become the main conducting paths in the current sheath. It is as if the current sheath senses the authority of the Alfven limiting current of 17,000 $\beta\gamma$ amperes and generates its own local B_z's inside its filaments to circumvent this limit. A plasma focus will carry 10^5-2×10^6 amperes, far in excess of the Alfven current, especially with $\gamma=1$ and $\beta\ll1$ and each filament carries a current in excess of the Alfven limit. Nardi's analysis makes plausible arguments to show that the filament spacing is proportional inversely to the background B_θ field, and directly as the electron density in the sheath. "Shock heating," which was often on the tongues of those working with the Z and θ pinches, for the most part does not occur in the plasma focus sheath: The current sheath corrugates and the directed energy that would ordinarily be degraded to entropy (thermal energy) in a planar snowplow or shock appears as rotational energy and local B_z and local B_θ energy of the vortex filaments. Indeed each one of these vortex filaments is a miniature B_z stabilized pinch that exhibits no $m=0$ or $m=1$ instability, *keeps* its sharp boundaries for several microseconds if need be, and maintains a respectably low resistance (no anomalously high resistance) as long as the filament remains intact. The stability properties of these vortex filaments are thus vastly superior to all of the man-made B_z stabilized pinches produced by the concerted international efforts on stabilized pinches from

FIGURE 10



Dissected diagram of the vector configurations of a pair of paramagnetic vortex filaments formed in the current sheath of the plasma focus; v is mass flow velocity, b is local magnetic field, j is current density, ω is vorticity, B_Θ is background magnetic field caused by flow of current in the coaxial electrodes.

FIGURE 11



a) *5 nanosecond profile view image-converter photograph of the vortex filaments lying in the grooves of the corrugations of the current sheath: The 3.4 cm-diameter positive center conductor (solid copper cylinder) can be seen. Background filling pressure is 8 Torr of deuterium; peak current is 0.5 Megamperes. Note how filaments fray at the outside end, like the end of an old rope.* ***b)*** *Axial view at moment of maximum pinching with 11 kilovolt operation. (Solid copper conductor)*

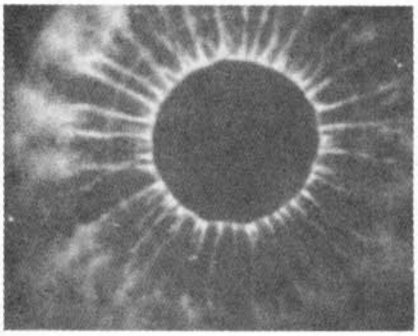
1953 to 1963. The success of these filaments lies in the fact that they have been permitted to develop their own mass rotation (vorticity) and mass axial flow in their own force-free way.

The vortex filaments are subject to frailties: They fray, like an old rope, at their ends near the outer conductor. (See Figures 11 and 12.) This phenomenon is analogous to the hydraulic jump and/or vortex breakdown in fluid mechanics. One way in which the local B_z field of the filament leaks to the region outside the filament is by the fraying process that can occur occasionally along the length of the filament as well as at its end.

As the pinching stage is approached by the current sheath (at the end of the center conductor), the overall radius of the

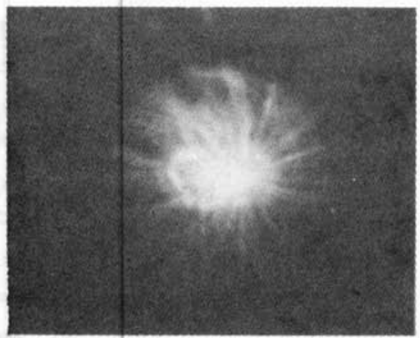
FIGURE 12

a



b

c

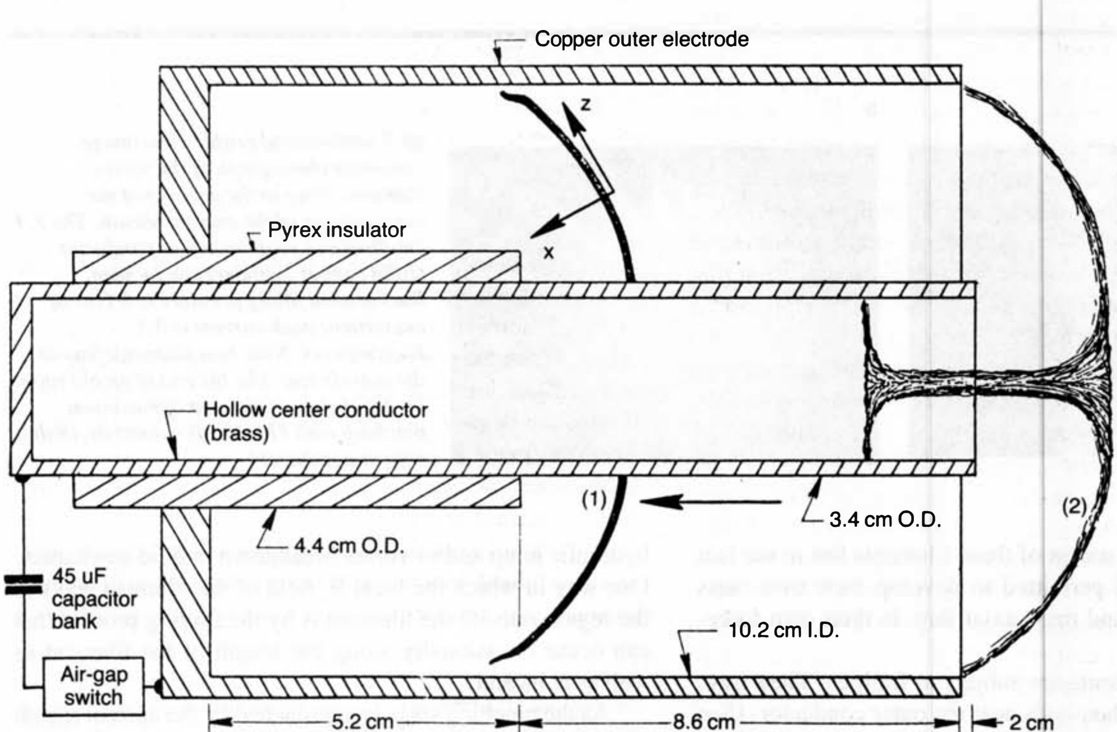


***a)** 5 nanosecond axial view image-converter photograph of the vortex filaments lying in the grooves of the corrugations of the current sheath. The edge of the 3.4 cm-diameter positive center conductor can be seen. Note how filaments fray at the outside end. Filaments (with pairing) can be detected. Center conductor (anode) is solid.*

***b)** Oblique view of current sheath with filaments with a hollow center conductor (anode).*

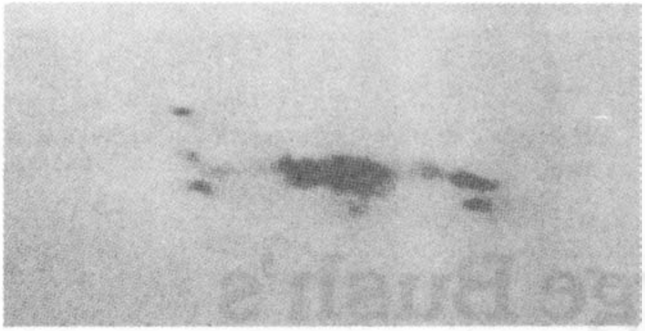
***c)** Same as 12b, but at a later time when vortex filament destruction is proceeding in the halos. Hollow center electrode (anode). In all three discharges, the background filling pressure is 8 Torr of deuterium; peak current is ~0.5 megamperes.*

FIGURE 13



Schematic cross-section of coaxial plasma focus with a hollow center electrode. The plasma focus acts as an accelerator moving the current sheath (1) from left to right. When the current sheath comes to the end of the electrode, it forms a stationary plasma pinch (2). This plasma pinch is the halo in Figure 12 and it is the pinch that neutrons and X-rays are generated.

FIGURE 14



X-ray pinhole camera photograph (negative image, single shot, time-integrated) of the region of the plasma focus for a hollow-centered conductor (anode) 3.4 cm in diameter, where no copper vapor interferes with the image of the X-rays coming from the deuterium gas filling. 50° from axis, pinhole diameter 0.16 mm, 0.05 mm Be absorber (ε≥2 Kev). Note multiple X-ray sources in off-axis region .p-8 Torr deuterium with 1% Ar. Neutron yield 0.84×10⁸. This photograph was taken with a distance pinhole-to-source of about 76 mm, pinhole-to-film 40 mm (maximum voltage on the electrodes 15kV). The source position is considered to be on the electrode axis, 8 mm above the center electrode end.

FIGURE 15

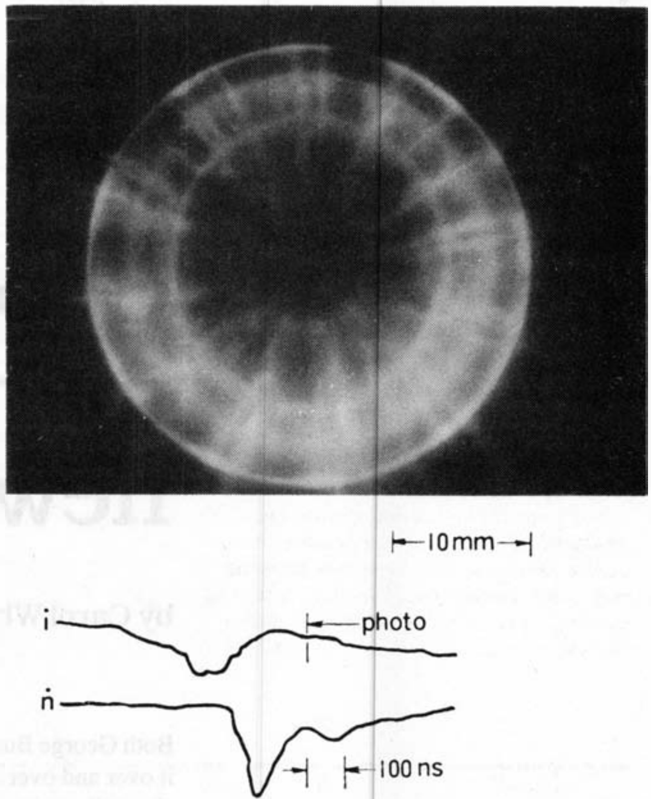


*Photo taken 300 nanoseconds later than the **I** peak. Note that neutrons are being produced and the pinch has vanished completely. The bright regions show vortex filament pairs combining in both halos (inside and outside the center conductor) as the circles travel radially outward. The "circles" are the intersection of a spherically shaped shock wave with the current sheath.*

gross current-carrying column is reduced, and this gives rise to a back emf($-$I(dL/dt)) that brings about some reduction in the current (a peak in the oscilloscope trace). Also, as the flow of neutral gas into the current sheath stops at the pinch stage, the filaments are permitted to come together and it can be observed that the right-handed and left-handed filaments start to annihilate each other, much as a fuse burns along its length. The author believes that this is a demonstration of the solar flare phenomenon that occurs in the laboratory. There are accompanying soft X-rays (<5 kev) and sometimes some neutrons. By image converter photos this annihilation process can be observed to occur in both the axial region and the umbrella (or halo) region of the plasma focus.

The very high $|\dot{I}|$ peaks at "pinch time" and the very high voltage peaks on the electrodes (5 times the voltage originally applied) are very likely due to the rapid destruction of these current-carrying filaments with their local B_z's. It is as if the "superconducting" filaments had suddenly lost their superconductivity; since their local B_z's have been destroyed, they must suddenly face the authority of the Alfven limit. A soft X-ray pinhole photo (50 micron Be screen, E>2 kev, time exposure) of this region of filament destruction is shown in **Figure 14.** Note the destruction in the halo regions as well as the axial region. Figure 12c and **Figure 15** show 5 nanosecond image converter photos of the filament annihilation occurring in the halos both inside and outside the hollow center conductor. The high $|\dot{I}|$ peaks and high voltage peaks on the electrodes of the plasma focus device are very similar to the phenomena observed in the turbulent heating experiments, but in the plasma focus the ion and electron densities and energies are high enough so that the *structures* of the plasma can be photographed by X-ray pinhole photography. Therefore in the plasma focus experiment one is not obliged to be content merely with the citation of some probable instability; one can visually observe the plasma "do its own thing." The writer believes that a true understanding of anomalous resistivity must involve a recognition of the role of these plasma vortex structures.

*Editor's Note

Because there are references to figures from last week's installment, the numbering for the figures in each installment will be consecutive throughout the series—that is, the first illustration in this installment begins with Figure 6.