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The Pinch Effect Revisited

by Winston H. Bostick

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Inaugural Note

The International Journal of Fusion Energy begins publication under the initial aegis of the Fusion Energy Foundation in what the editors hope will become a worthy new source for the progress of plasma physics (as part of the self-ordering behavior of most aspects of the universe!) The Journal, like its plasma subject matter, started out and continues in a state of healthy flux, with the scientific editorial board still in formation and the permanent publishing arrangements of the quarterly still to be finalized.

It has been said that the canonical conceptions of fusion physics are stability, transport, and confinement. If this is so, the IJFE has much conceptual space to fill beyond these established areas, most importantly in the realm of fundamentally nonlinear effects. This journal is intended to provide a forum for the kind of imaginative and even speculative concepts in plasma physics — so long as these are ultimately subject to the test of "crucial experiment" — that are necessary for the future growth of this infant science. With a combination of retrospective reviews and rigorous new results presented in light of their conceptual significance, the IJFE is born.

In line with these goals, this introductory issue of the journal presents a historical view of one area of plasma physics by a self-described "old-hand" in CTR, Professor Winston Bostick. The editors fully concur with Dr. Bostick's assessment of the importance of midwifery for the "Pasteur era" of plasma physics.

Finally, we remind readers that the success of the journal depends on your subscriptions. Subscription information for the IJFE quarterly appears at the back of the journal.

The Pinch Effect Revisited

Dr. Winston H. Bostick

The pinch effect is the self-constriction of a column of deformable conductor which is carrying an electric current. The constricting effect on the column is produced by the magnetic field pressure resulting from this current, or equivalently, by the Lorentz force produced by the current flowing in its own magnetic field. Thus, in a CTR magnetic-containment device of the pinch-effect type, the containing magnetic field is generated chiefly by the currents flowing in the plasma itself.

In the sixteenth century the effect of a Lorentz force on a movable, deformable plasma conductor was observed by William Gilbert, the court physician to Queen Elizabeth I of England: He noted that a candle flame was deflected away from a magnet when the magnet approached the flame. J. A. Pollock and S.H. Barraclough at the University of Sydney reported in 1905 an analysis on a piece of lightning conductor (a 1.8 cm-dia, 0.1-cm-wall-thickness copper tube) which had passed a lightning bolt about the year 1895. *(1)* The copper tube had been crushed by the "electrodynamic action of the current," and if the tube was assumed to be rigid (not softened to plasticity by the heat) at the time of the passage of the current, it could be calculated that the magnetic pressure had been about 400 lbs. per sq. in., and the current had been about 100,000 amperes. Photographs of the cross-section of the crushed cylindrical shell are shown in Figure 1. Indeed a lightning stroke in the atmosphere is a column of plasma whose diameter is influenced in some measure by the pinching electromagnetic forces.

In 1933, (when the neutron was being discovered and Hitler was on the rise to power), Willard Bennett wrote his famous paper on the steady-state pinch effect (published in 1934). *(2)* This article treated in a relativistically correct way the effect of the mutual attraction of electrons moving in one direction and the positive ions moving in the opposite direction. The correct relationships showing how the electric charge density depends upon the frame of reference (relationships developed independently again by Budker in his doctoral thesis in 1956) were set forth by Bennett. Bennett calculated the equilibrium radial electron (and ion) density distribution to be

$$n_e = \frac{n_o}{[1+(r/r_o)^2]^2},$$

where

$$\mu_o e^2 r_o^2 n_o v_z^2 = 16kT$$

and

$$\mu_o I_o^2/8\pi = NkT \text{ (mks units)},$$

$$B_z = O,\ p = n_e kT_e + n_i kT_i,$$

$$T = (T_e + T_i)/2.\ I_o$$

is the total current,

$$N = N_e + N_i \cong 2N_e =$$

the number of electrons and ions per unit length of column, v_z is axial electron drift and is constant everywhere, k is Boltzmann's constant, e is the electronic charge. It is rather

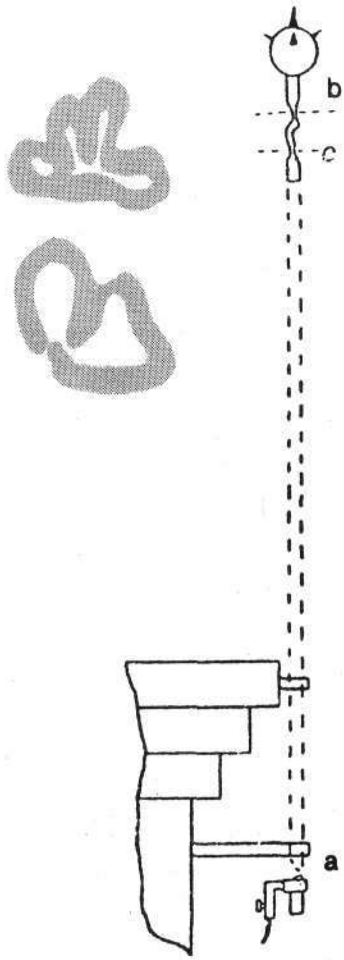


FIGURE 1

Drawings of the cross-sections of the copper lightning rod that was crushed by the passage of a lightning bolt.

incredible that such a sophisticated and perceptive paper on this phase of plasma physics should appear all by itself at this early date.

About ten years later experimental work on the pinch effect in plasmas commenced with some work by Steenbeck, who worked on induced, pulsed, high currents in a ring-shaped glass tube. Cousins and Ware *(3, 4)* at Imperial College in England performed experiments of this type *(5)* from 1947 to 1951 and "were the first to demonstrate" that the current channel (10^4–2×10^4a) did constrict. In 1951, due to security classification, this work was transferred to AEIRL at Aldermaston where extensive development was carried on in the problem of arcing between the segments of the metallic liners used in their discharge tubes. *(5)* The employment of the applied magnetic field (in 1953) in the direction of the pulsed current led to the SCEPTRE program. Bill Baker at the Lawrence Berkeley Lab (formerly the University of California Radiation Lab) in 1951 produced a pulsed, pinched high current (10^5a) discharge between two electrodes in H_2 gas and photographed the constricted ($\sim$3mm dia) channel. Security classification prevented Baker's work from being published at that time. About 1950 at Los Alamos, planning of experiments (the Perhapsatron) on the pinch effect got underway under the direction of James Tuck. *(6, 7)* Apparently the Soviets also started work on the pinch effect about the same time: The work on the H bomb in the USA, USSR, and United Kingdom had by this time rekindled enough interest in controlled thermonuclear research to get some experimental CTR programs underway at the security-classified weapons laboratories in these countries.

Levine, Combes, and Bostick at Tufts University showed in 1952 and1953 that an 8,000-ampere pulsed current in low pressure nitrogen gas produced a pinch which concentrated the spectral line emission from singly ionized nitrogen, and concentrated even more the lines from doubly ionized nitrogen. *(8)*

In June 1952 at a meeting of the American Physical Society in Denver a special session on CTR was held under security classification for those interested physicists who held the appropriate security clearance. The "Matterhorn" project from Princeton University under Lyman Spitzer described their concept of the stellarator with its figure "8" configuration to obviate the "grad B drift," and presented, in brief, the theoretical work of Kruskal and Schwarzchild in which they predicted the sausage ($m = 0$) and kink ($m = 1$) MHD instabilities that the pinch effect would be expected to be subject to *(9)* (see Figure 2). These instabilities were similar to the Rayleigh-Taylor instabilities of fluid mechanics and could be classified as MHD instabilities because the pinched fluid was

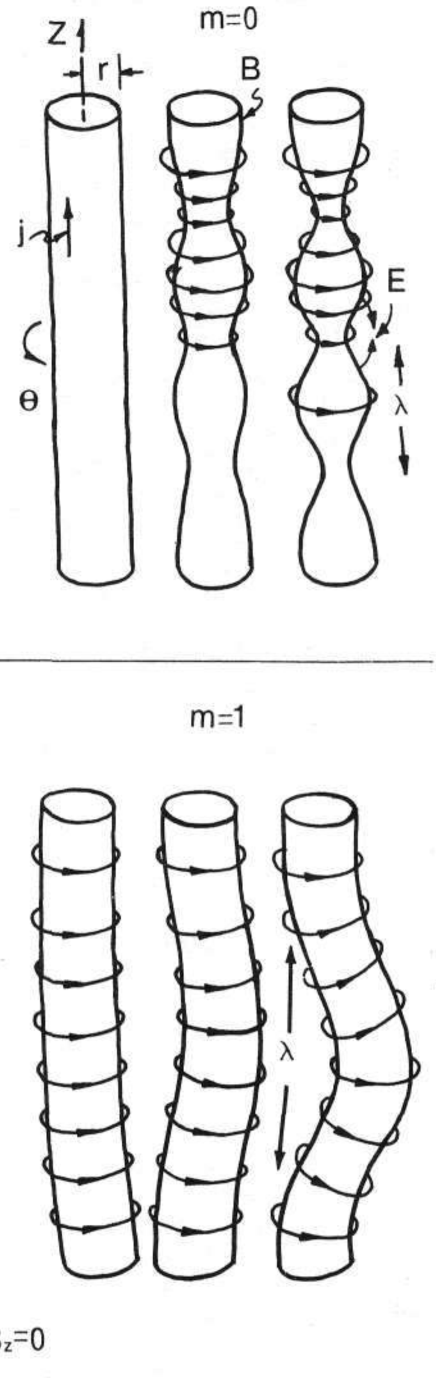


FIGURE 2

Diagrams of the m=0 (sausage) instability and (m=1) kink instability to which the pinched column of plasma carrying a current density j is subject. These are MHD instabilities. The axial magnetic field is $B_z = 0$.

largely regarded as an MHD fluid in the treatment. The e-folding time for such instabilities was calculated to be a characteristic dimension divided by the sound speed in the medium, where the characteristic dimension was the geometric mean of the pinch diameter and the wave length of the instability. At this meeting the Livermore CTR group discussed the concepts of its mirror machines and also the possibility of RF confinement. James Tuck *(6,7)* and W.H. Bostick *(8)* made a few remarks about the pinch effect and Herbert York *(10)* showed a few of the pinch-effect photographs taken by Bill Baker at Berkeley. Victor Weiskopf asked the question "Just what is this pinch effect," whereupon George Gamow (always in a jocular mood) approached Weiskopf from behind and pinched him. Van Allen, who was at the time involved in the leadership of Project Matterhorn, expressed great skepticism about the pinch effect and stated that none of the evidence thus far presented had convinced him of the existence of the pinch effect. Thus ended that session in 1952.

1954-63: Practical Schemes

To locate the pinch effect among the various animals in the CTR zoo we must recognize that the bulk of CTR thinking has traditionally reasoned that the pinch-effect magnetic field will impart energy to the plasma by adiabatic compression (in the dynamic pinch), by shock heating, by Joule heating, and by various instability mechanisms, and that in these processes the plasma can be expected to acquire an energy density approximately equal to that of the magnetic field.

In the experimental investigation of the translation of this magnetic field energy into plasma energy it has appeared that the plasma becomes more difficult to confine as it absorbs the energy; that is, the instabilities grow more rapidly in the energetic plasma, and the instabilities will very quickly and prematurely result in a loss of the plasma and its energy to the wall of the vacuum chamber.

On the other hand, a successful CTR magnetic containment device must have an energy containment time τ and an ion density n sufficiently large so that an appreciable fraction of the fusionable fuel will be burned; that is the Lawson criterion must be satisfied ($n\tau > 10^{14}$ for a DT reactor). In the ordinary dynamic pinch, that is, one with no axial (longitudinal) magnetic field, B_z , it was concluded that the magnetic energy goes very rapidly into the development of instabilities which dump the plasma and its energy from the containing column to the walls before the fuel has an opportunity to burn. Thus, at a fairly early date (about 1954-55 in the USA, perhaps earlier in the USSR and United Kingdom) there were growing suspicions that the ordinary dynamic pinch was unsuitable for a practical thermonuclear fusion reactor.

Accordingly, from about 1954 through 1963 a vigorous effort was mounted in the international CTR community to devise a practical scheme employing axial magnetic fields, conducting walls, r-f fields to stabilize the pinched plasma column long enough to permit an appreciable fraction of the fuel to react.

The quantitative concept of the transient pinch as being a process of heating the plasma by an adiabatic compression was generated in the USA by Levine, Bostick, and Combes and transmitted in a letter to Lyman Spitzer in 1953. The stabilizing effect of a conducting copper coating outside the glass-walled pinch vessel was also recognized in the USA by Levine and Bostick quantitatively in a letter to the Matterhorn group in 1953. These same ideas undoubtedly occurred independently at about the same time or earlier to other workers in the USA, United Kingdom, USSR, and elsewhere. Because of security classification there was no systematic reporting in the journals.

In 1954 Bostick went to work at LLL, but Levine, remaining at Tufts, demonstrated experimentally that an enclosed axial magnetic field (B_z) would stabilize the $m = 0$ (sausage) and short wave length $m = 1$ (kink) instabilities of the pinch effect. Levine *(11)* gave a paper on this work at a classified CTR meeting in Princeton in 1955 at the same meeting when Rosenbluth *(11,12)* gave his theoretical paper on the stabilizing effect of a trapped axial magnetic field in the pinch. Rosenbluth showed theoretically that the pinched radius must be kept larger than one-fifth of the radius of the return conductor shell and the plasma pressure must be low compared to $\frac{B_z^2}{2\mu_0}$. The region containing the hot plasma and the B_z field must be sharply bounded from that containing the B_θ pinch field. These are the conditions necessary for stability against the $m = 1$ mode.

Figure 2 shows the sausage ($m = 0$) and kink ($m = 1$) instabilities which develop in the pinch effect when there is no B_z, or axial magnetic field, either inside or outside the pinched column. The MHD instability analysis investigates the stability of the pinch against perturbations of the form Re (exp) $i(\pm m\,\theta + kz)$. k is the wave number of the perturbation in the z (axial) direction and m is the wave number of the perturbation in the θ direction. Figure 3 shows the form of these perturbations when $B_z \neq 0$. Figure 4 shows typical experimental arrangements for the pinch (linear and toroidal).

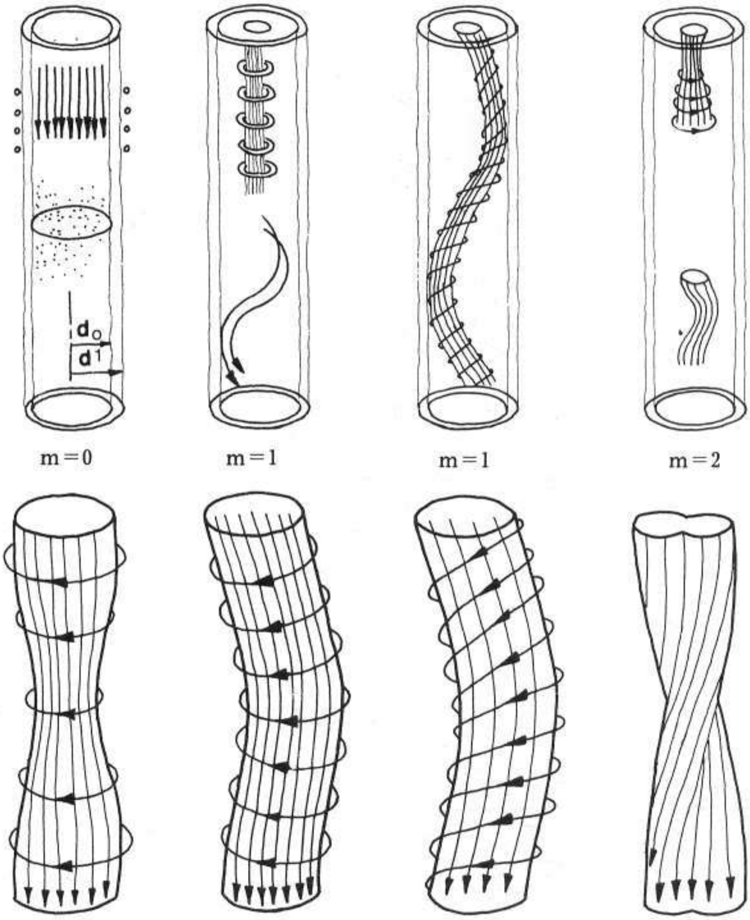


FIGURE 3

Diagrams of the m=0, m=1, and m= 2 perturbations when $B_z \neq 0$ and there is a conducting metallic coaxial return conductor. The applied B_z can be trapped inside the column or it can be both inside and outside the column.

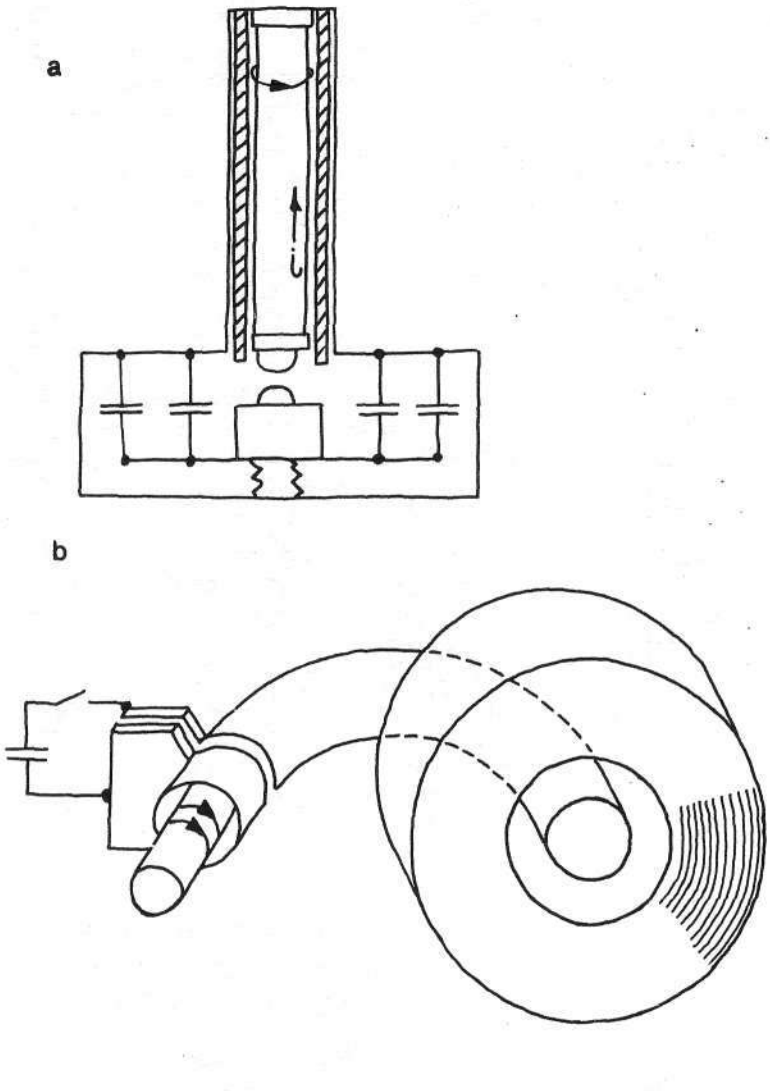
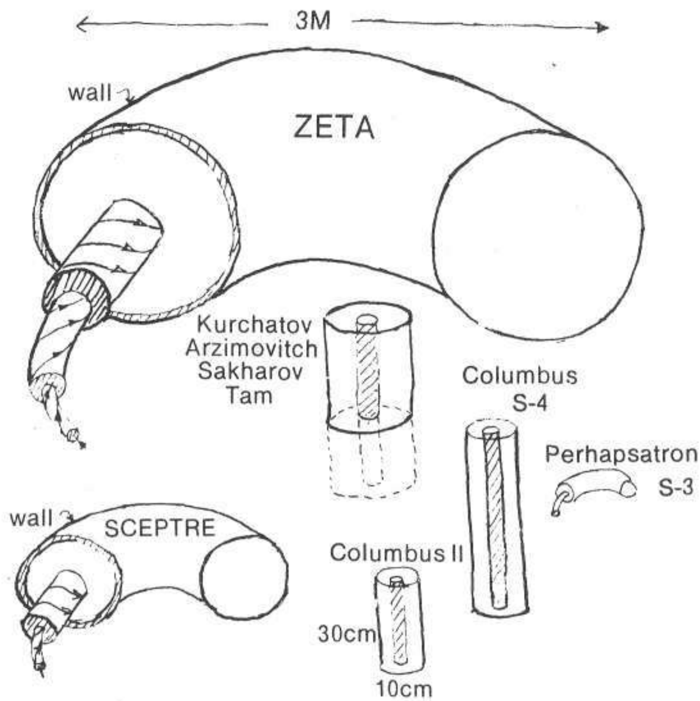


FIGURE 4

Typical geometries for pinch-effect apparatus:

a linear pinch,

b toroidal pinch.



	Energy Storage	Half-Cycle time	Maximum current	B	Neutrons per pulse	T from Neutron yield	T from Doppler
ZETA	$5x10^5$ J	4ms	84-187 KA	160-400g	0.4-$134x10^4$	$4.6x10^6$ °K	$3x10^6$ °K
SCEPTRE	$7x10^4$	400μs	20-200 KA	100-1000g	10^3-10^5	2-$3.5x10^6$	2.5- $3.8x10^6$
COLUMBUS II	10^5	4μs	1-$2.5x10^6$A	0-10^4g	$2x10^7$ B 0, $3x10^6$ B 23,	$2x10^4$	B_z \= 200
COLUMBUS s4	$1.5x10^4$	12μs	$2.5x10^5$A	0-1750g	10^3-10^5		
Beybatchenko Golovin USSR	$1.4x10^5$	30μs	$7x10^5$ A	0-12000g			
Perhapsatron s3	$4.4x10^4$	12μs	$2.3x10^5$A	0-4000g	$2x10^5$-10^6		
Kurchatov USSR	$3x10^5$	6-60μs	$2x10^6$ A				
Sweden	10^5	10μs	$3x10^5$	0			

FIGURE 5

Collage of some of the pinch menagerie, circa 1956.

Figure 5 is a kind of collage of these various early pinch schemes. Figures 2-5 were sketches made about 1956 by the author who was then contemplating writing a book on CTR.

In 1954 Rosenbluth and Garwin in a classified Los Alamos report came out with their famous report on their "M" theory (M stands for motor) in which they used Maxwell's and Newton's laws to compute the time that it should take for the pinch effect to collapse. *(13)* They also produced the theory of the Rosenbluth sheath and in doing so they reinvented the Ferraro sheath which was developed by Ferraro in the study of the earth's magnetosphere.

In the Rosenbluth M theory the calculated velocity $\dot{r}$ for the radial collapse, as determined by Newton's second law and the Lorentz force, is $r \sim (E^2/\rho_m)^{1/4}$ where E is the applied electric field and ρ_m is the mass density of the ionized gas which is swept up in "snowplow" fashion by the current sheath. The thickness of the current sheath is calculated to be c/ω_p where ω_p is the plasma frequency and c is the speed of light. In actuality the observed current sheath thicknesses are usually 10 to 100 times this value. Furthermore, as will be shown later (1966), the current sheath is **not** purely planar or purely cylindrical but it corrugates in the two directions which are parallel and perpendicular to the applied magnetic field. Plasma vortex filaments are observed to lie in the grooves of these corrugations and the current sheath is really a tissue made up of these vortex filaments. Thus, the M theory which can be used to compute effectively the gross dynamics of the time for collapse for the linear pinch and the gross shape of the plasma-focus current sheath (Potter's code, for example) is a kind of a myth in a plasma focus as far as the fine structure of the current sheath itself is concerned. *(14)* And indeed the famous 1934 Bennett theoretical, steady-state pinch is, in actuality, also a myth: It is never achieved because of the instabilities which destroy it or the vorticity which modifies it.

Stirling Colgate joined the CTR movement in 1954 at LLL and was fascinated with Rosenbluth's work. Colgate set up an MHD experiment with liquid sodium where he demonstrated quantitatively that the sausage and kink instabilities did develop, that is, that the MHD, Rayleigh-Taylor instabilities were there.

By this time the Perhapsatron at Los Alamos and the toroidal pinch *(4)* in the United Kingdom were showing the sausage and kink instabilities and the project Columbus I was underway. *(6,7)* Columbus I was an attempt to produce a pinch effect in a high current discharge between two electrodes in deuterium at about 100 microns pressure, in an apparatus like

Figure 4. The famous E. O. Lawrence of Berkeley happened to be visiting Los Alamos and saw their experimental setup for Columbus I and heard their tale of woes about cracking glass tubes and leaking seals. He recalled that his highly talented group under Bill Baker at Berkeley had already worked at the pinch effect, and when he returned to Berkeley he put Baker back to work on the pinch effect apparatus similar to that used for the results reported by Herbert York at Denver in 1952. *(10)* In about two months of work Bill Baker's group was observing x-rays and the 2.45 Mev neutrons, $D(D,n)He^{3}$, from the pinched discharges in deuterium gas at about 100 microns pressure.

At that classified CTR meeting in Princeton in 1955, at which Levine presented his results on the H-centered (B_z-stabilized) pinch, Baker gave his results on the neutrons and x-rays from the linear (z) pinch. *(15)*

After Baker's presentation the author recalls hearing one representative from Los Alamos remark in a private discussion that he felt it was "highly unethical" for Berkeley to have started work, under Lawrence's stimulation, on the pinch effect at that time: Los Alamos had no such spectacular results on the pinch effect to report at that meeting, and at least one of their investigators obviously was piqued at being upstaged so suddenly by the Berkeley lab in so important a CTR role as pinch effect research. The experimenters at Los Alamos, emboldened by Baker's results, went back to their lab after that Princeton meeting and soon they were producing neutrons with Columbus I and II.*(7,16)* Furthermore, so heady was the wine of their first success that they were wont to assert that these neutrons were very likely true thermonuclear neutrons, and not those produced by a process which electrically accelerated deuterons into deuterons. Colgate at Livermore undertook, with the help of Berkeley's nuclear emulsion scanners, a detailed comparative analysis of the knock-on proton tracks obtained from the neutrons proceeding from the anode-to-cathode and cathode-to-anode directions of the Columbus I pinched discharge. *(15)*

Colgate's results showed clearly that the neutrons proceeding in the anode-cathode direction were, on the average, definitely of higher energy than the neutrons proceeding in the cathode during the pinch, and, therefore, that deuterons were average, the center of mass of the pairs of reacting deuterons in the reaction $D(D,n)\ He^{3}$ was moving from the anode to the cathode during the pinch, and, that therefore, deuterons were being accelerated in the anode-cathode direction and reacting with other deuterons which had not been so accelerated and were thus acting as targets. It was hypothesized that a rapidly pinching sausage instability in the channel produced a high back electromotive force ($\cong -I\,dL/dt$) and that the resulting choking of the current built up a high positive potential toward the anode and a high negative potential toward the cathode end of the pinched channel. (Such high voltage spikes from the back EMF could be seen on the oscilloscopes which recorded the voltage signals from capacitance dividers.) These high potentials were thought to be able to accelerate a few of the deuterons into other deuterons to produce the neutrons. X-rays (approximately 5 kev to 200 kev) were also generated simultaneously with the neutrons. At any rate the results showed that energetic deuterium ions (and electrons) did not represent a thermal ensemble, and therefore the fusion reactions were judged to be **non**thermonuclear and hence theologically "impure" as far as the CTR program was concerned. These results were a chastening blow to the ardor of those people working on the pinch effect at Los Alamos.

During the highly limited unfolding of this security-classified story in the USA there occurred a dramatic international announcement, exceeded in its spellbinding effect only by the explosion of the bombs at Hiroshima and Nagasaki (with the subsequent Smythe report) and the announcement of the successful H bomb detonations. In 1956 Khrushchev and Kurchatov (after whom is named the Kurchatov Institute of Atomic Energy in Moscow) appeared for a visit at the Atomic Energy Research Establishment at Harwell in the United Kingdom. *(17)* The press throughout the world carried front page pictures of Khrushchev and Kurchatov in white laboratory coats inspecting the various sites at Harwell because Kurchatov, in a prepared speech before the United Kingdon scientists assembled at Harwell, proceeded to describe in considerable detail the results of the pinch effect research in the USSR. One must recognize that the pinch effect research at this moment was not a side show to a CTR circus involving the stellarator, Ogra, mirror machine acts; the pinch effect was **the** featured show in the **main ring.** The Soviet results told of neutrons and x-rays and voltage spikes from their pinch effect apparatus which was similar to that in use in the USA. The Soviets had found that the neutrons came from a nonthermal process, their work was accurate, highly detailed, well planned, well instrumented. Lewis Strauss, then the Head of the USAEC, made the response to the press that "The Russian results do not tell us anything we have not known for some time." Strauss' adverbial phrase, "for some time" covered up the fact that the U.S. pinch effect research had arrived at the same conclusion as the Soviets by a margin of only a few months. It could be estimated that the Soviets had been producing such results since about

1953, and the U.S. effort compared to the Soviet was rather thin. One might surmise what Lewis Strauss would have been able to say if E. O. Lawrence had not ordered Baker to get back on the pinch effect research in 1954 and if Stirling Colgate had not insisted on analyzing the neutron energy.

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. *(18,19)* The USAEC 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 USA agreed to exchange CTR information.

The forthcoming IAEA Atoms for Peace Conference in 1958 at Geneva was the occasion for Lewis Strauss 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 USAEC 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. *(20)* 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 wave lengths, 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 *(20)* theoretically that the mean plasma temperature over a skin depth in from the pinch surface is about

$$T_r = {}^1\!/_3\, T_c = H^2 / 24\pi\, nk$$

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 temperative.

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 $T_r = {}^1\!/_3\, T_c$, 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 3000 ev, the electron temperature calculated from electrical conductivity measurements was $T_e \cong 10\,\mathrm{ev}$. 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. *(20)* 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 USA, United Kingdom and USSR as an extension of this work. *(21)* 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 D_2), and microwaves, similar to what happens in the ordinary dynamic pinch at the time of pinching.

The United Kingdom's SCEPTRE *(5)* and later the large toroidal ZETA apparatus at Harwell and Culham were stabilized pinches on a large scale (large diameter, approximately 3m for ZETA). *(22)* (See Figure 5.) 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 USA, USSR, United Kingdom, France, and Sweden.

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 fusion 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. *(23)* The conventional pinch effect produced between the two "conventional" electrodes as

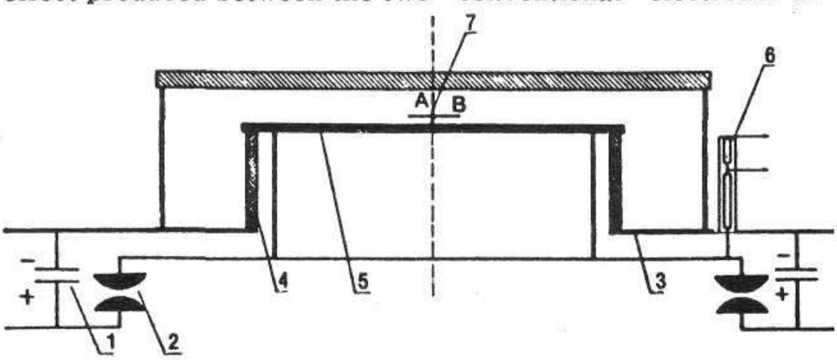


FIGURE 6

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)

shown in Figures 2 and 4 (and in Columbus I and II) can produce a maximum of about 10 neutrons per pulse with a filling of about 100 microns of D_2. The Filippov-geometry pinch operating in D_2 at a pressure of a few Torr produced about 10^{10} neutrons per pulse!

Kvartskava from Sukhumi in the USSR 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. *(24)* 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 the pinch (observed with a coil made out of metal screen). *(25)* The striations reported by Bodin were "explained" by Rosenbluth, Furth, and Kileen in terms of the finite-resistively driven instability in the tearing model. *(26)* 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. *(27)* 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 dia channel) circulation cells to be reported later by the Stevens group.

In 1962 Daniel Wells, working on his thesis at the PPPL, produced plasma vortex rings from a conical θ-pinch gun. *(28)* 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. *(29)* 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.

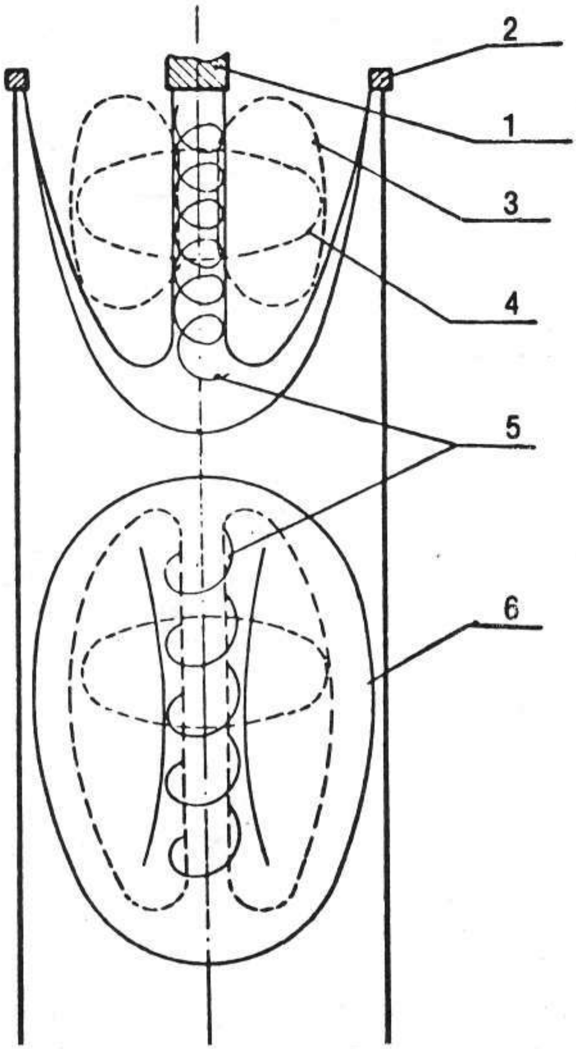


FIGURE 7

Diagram of circulation cells produced by Komelkov's fountain pinch. These circulation cells were believed to be force-free configurations.

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

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 *(30)*; the superb optical diagnostic work by Peacock's group at Culham *(31)* and the French group at Limeil *(32)*; the pioneer work on filaments at Sukhumi *(24)*; the work by Bernstein and others *(33,34)* 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 *(35-37)*; the work of Potter in computing the history of the current sheath during collapse *(14)*; the work of Beckner on x-rays from the plasma focus *(38)*; and the work by Luce and others at Aerojet Nucleonics in attaining large neutron yields. *(39)* The fine observational work on the pinch effect carried out with a Kerr cell by Curzon and others *(40, 41)* 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 APS Plasma Physics Division Meeting in Madison, Wis. in November 1971. Mather was invited to write the section on the plasma focus in *Methods of Experimental Physics. (42)* 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 focus machines: With Mather's insulator the current sheath breaks 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. *(43)* 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 *(44)*, 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 an NSF 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 LLL 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. *(45)* In 1964 image-converter photos taken at Stevens by Grunberger and Prior showed that similar diamagnetic vortices were produced in **pairs.** *(46)* 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 $\vec{E}=\vec{v}\times\vec{B}$ 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. *(45)* 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. *(47)* 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. *(48)* 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 *(49-51)* where they have been so identified in experiments at the PPPL, and by workers on the multipole machine at Wisconsin. *(52-55)*

In the experiments by Lovberg in 1963 *(56,57)* 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. *(45)* 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. *(46)* 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. *(46)* 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. *(27, 28)* The diameters (<1 mm) have been measured with image converter photography and the local B_z fields with coupling-loop probes. *(46)* 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_θ because they are traveling in a medium that develops a particular flow structure.

Figure 11 shows 5-ns-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

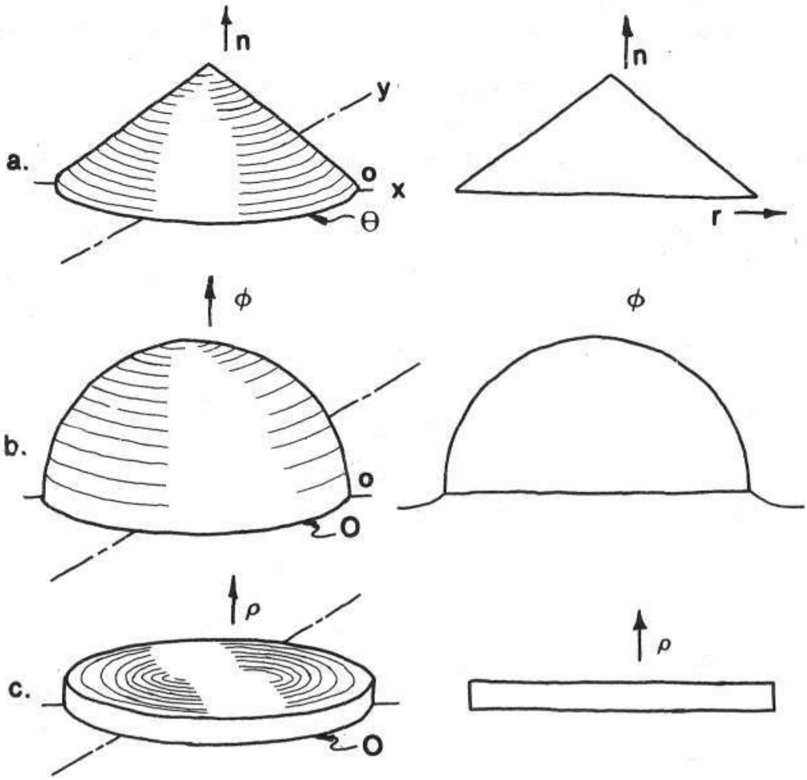
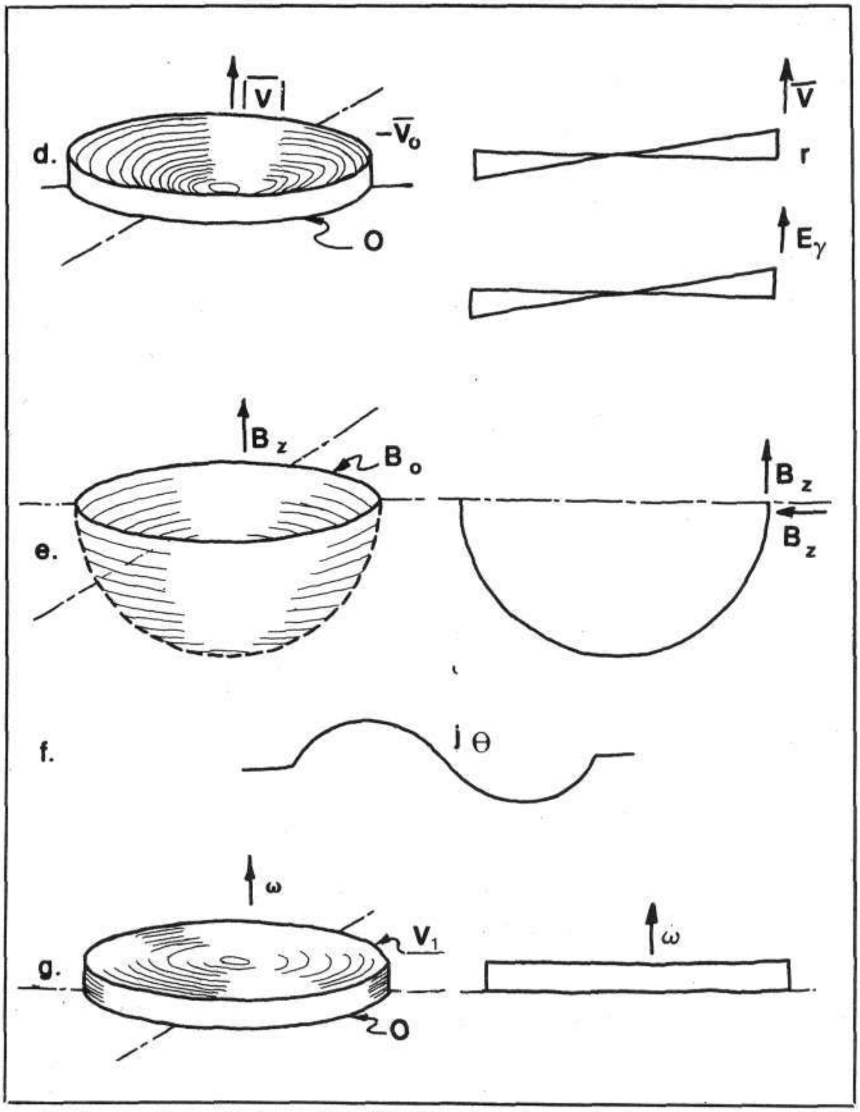


FIGURE 8

Profile plots 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.

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 ($\sim$5KJ) Stevens plasma focus.

Nardi has shown theoretically, from an MHD treatment, that if the current sheath of the plasma focus becomes corrugated vorticity can be expected. *(58)* 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. *(59, 60)* 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

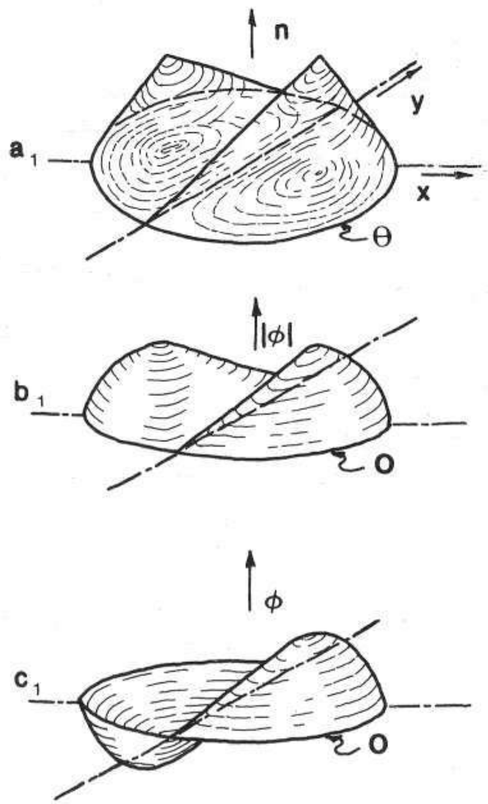
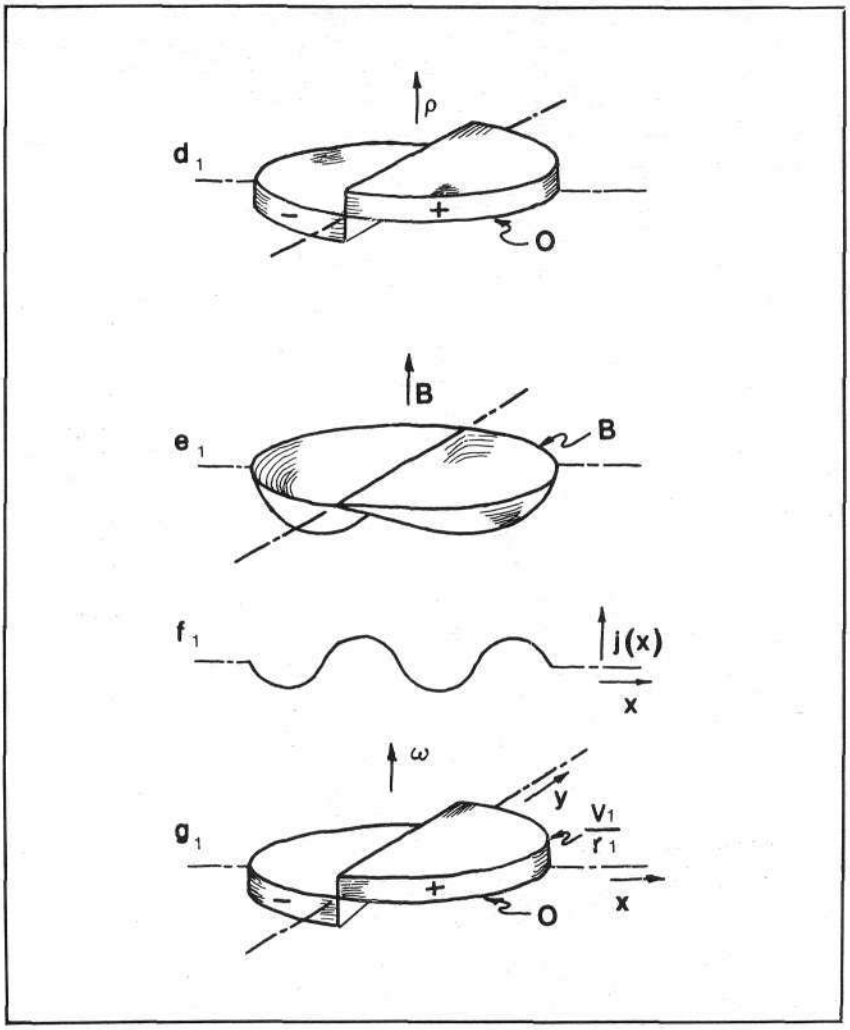


FIGURE 9

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

conductor. This resultant helical flow (right hand or left hand) along each pair of the filament 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 super-conducting 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 17000 $\beta\gamma$ amperes and generates its own local B_z's inside its filaments to circum-



vent this limit. A plasma focus will carry 10^5—$2\text{x}10^6$ amperes, far in excess of the Alfven current, especially with $\gamma = 1$ and $\beta << 1$ 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 current 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

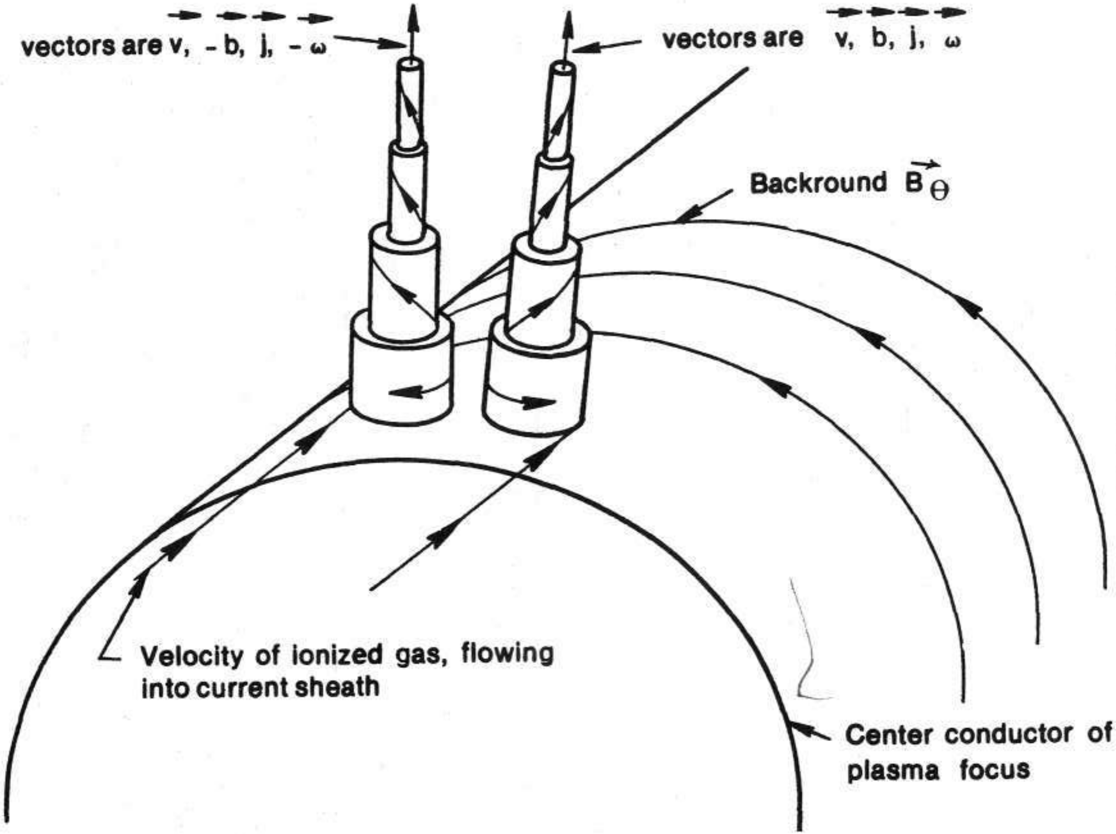


FIGURE 10

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.

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 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. *(61)* 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 gross current-carrying column is reduced, and this gives rise to a back emf $-I\frac{dL}{dt}$ 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. *(62, 63)* 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. *(60, 62)*

The very high $|\dot{I}|$ peaks at "pinch time" and the very high voltage peaks on the electrodes (5x 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 "super conducting" 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 ($50\,\mu$m 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. Figures 12c and 15 show 5 n sec image converter photos of the filament annihilation occurring in the halos both inside and out-

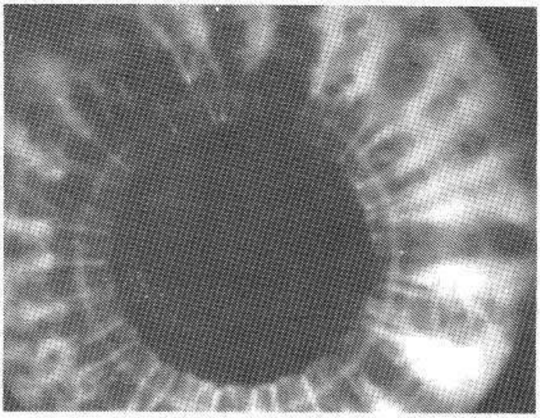
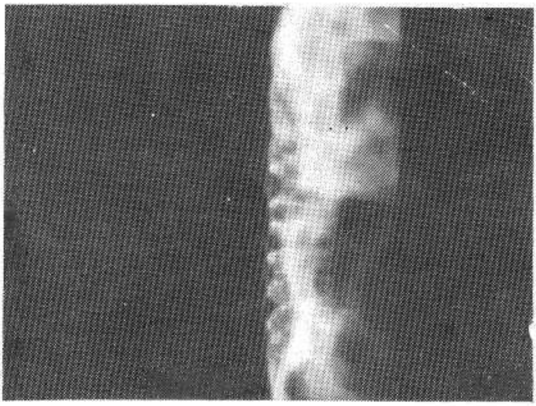


FIGURE 11

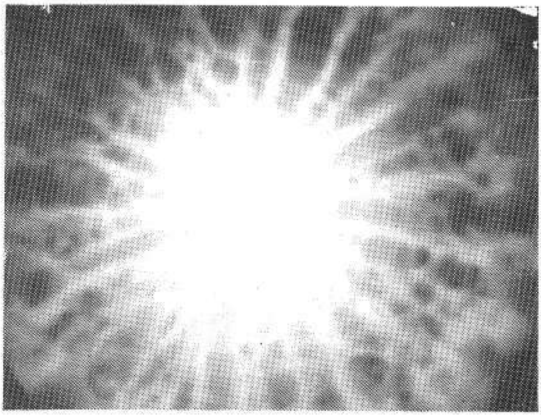
a

5 nsecond axial 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 Ma. Note how filaments fray at the outside end, like the end of an old rope.



b

Profile view of 11 a



c

Axial view at moment of maximum pinching with 11kV operation.

(solid copper conductor)

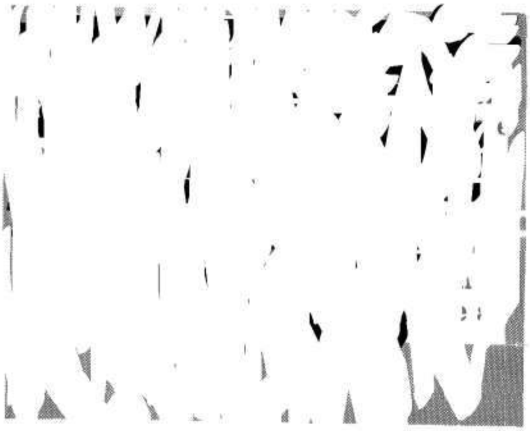
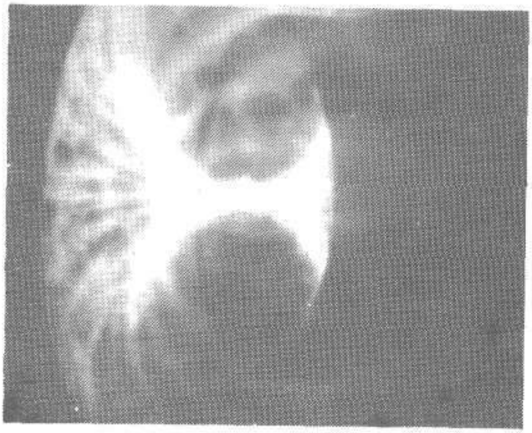


FIGURE 12

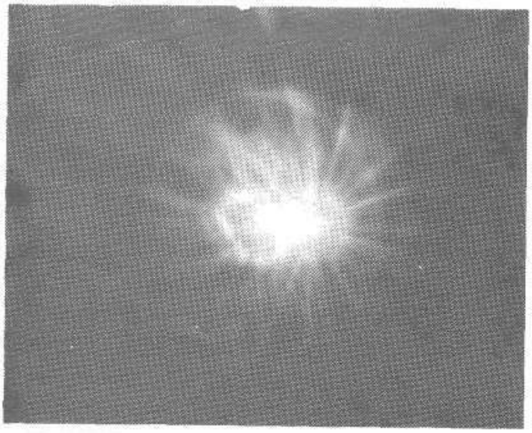
a

5 nsecond 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

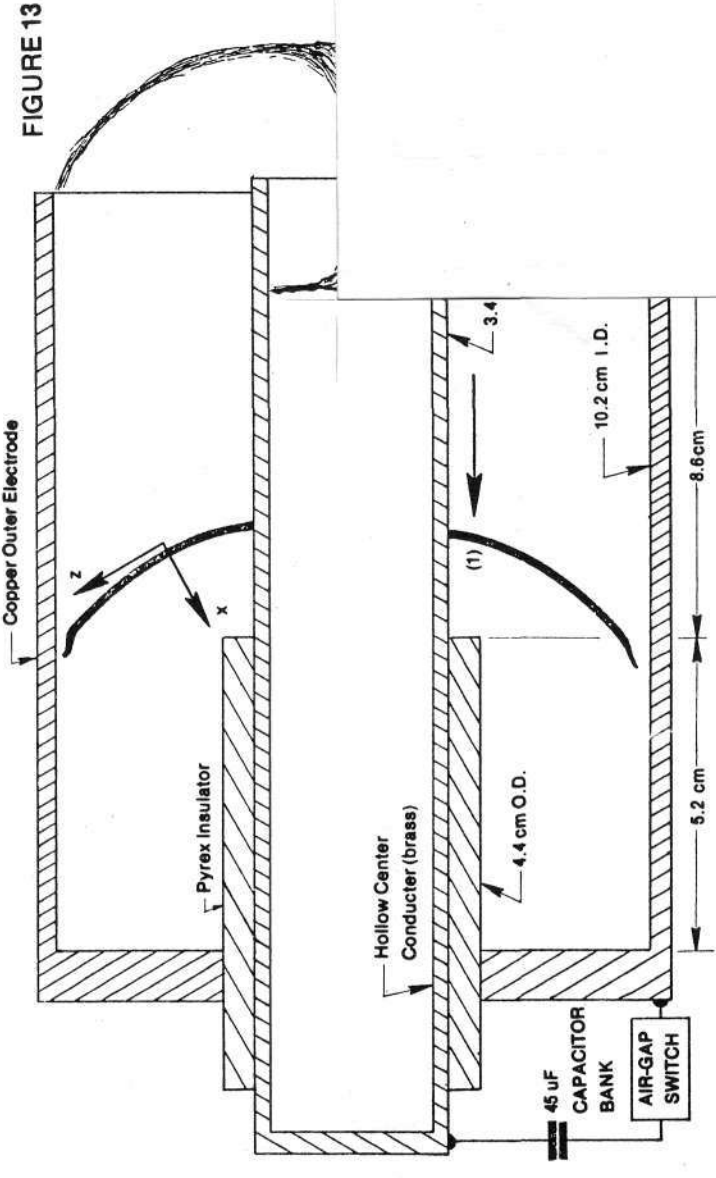
Oblique view of current sheath with filaments with a hollow center conductor (anode).



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 $\sim$0.5Ma.

FIGURE 13



Schematic cross-section of coaxial accelerator with a hollow electrode. The current sheath is shown (1) during motion betwe electrodes, and later (2) at the time of halo formation, when ne and x-rays are formed.

side 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 *(21)*, 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.

An x-ray pinhole photo (Figure 16) with a 50 μ Be screeen (>2 Kev) shows multiple intense spots imbedded in a softer, more widespread x-ray image. Photos with a paper and plastic screen (>7 Kev) but with a larger pinhole aperture show the multiple higher energy x-ray images. Pinhole photos taken with small pinholes (12 μm) to (50 μm) delineate the shape (like a bow tie or concave spool or apple core) and minimum dimensions of these images (50 μm dia, 400 μm in length). High-space-resolution pinhole photos end-on, along the machine axis, suggest that there are filaments emanating spoke-like from the ends of these x-ray sources.

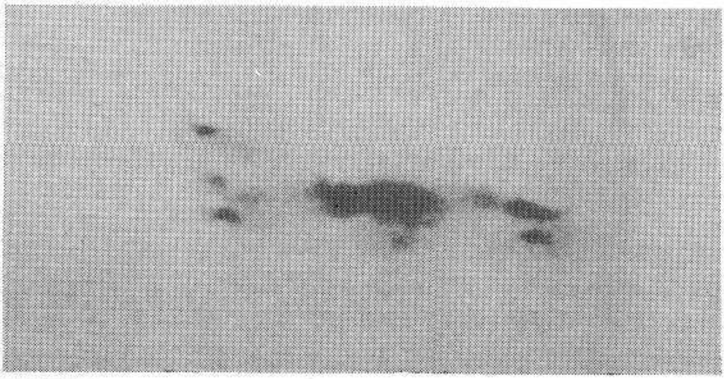


FIGURE 14

X-ray pinhole camera photograph (negative image, single shot, time-integrated) of the region of the plasma focus for a hollow-centered conductor (anode) 3.4cm in diameter, where no copper vapor interferes with the image of the x-rays coming from the D_2filling. 50° from axis, pinhole diameter 0.16mm, 0.05mm Be absorber($\epsilon \geq$2Kev). Note multiple x-ray sources in off-axis region.p-8 Torr D_2 with 1% Ar. Neutron yield 0.84 x 10^8. This photograph was taken with a distance pinhole-to-source of about 76mm, pinhole-to-film 40mm (maximum voltage on the electrodes 15kV). The source position is considered to be on the electrode axis, 8mm above the center electrode end.

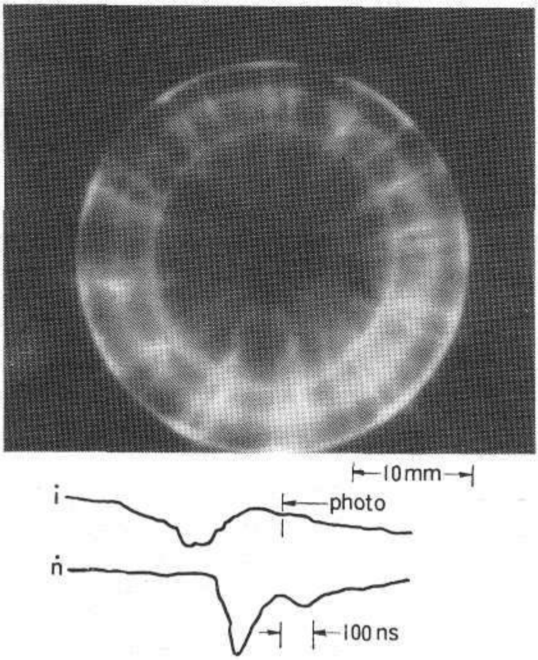
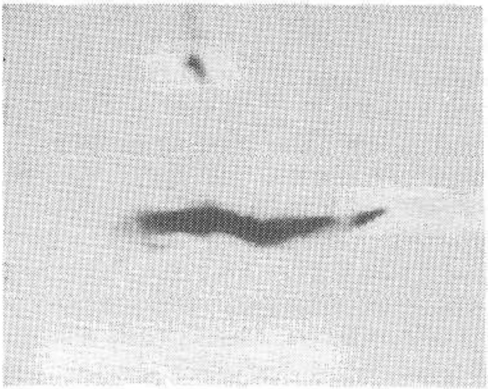


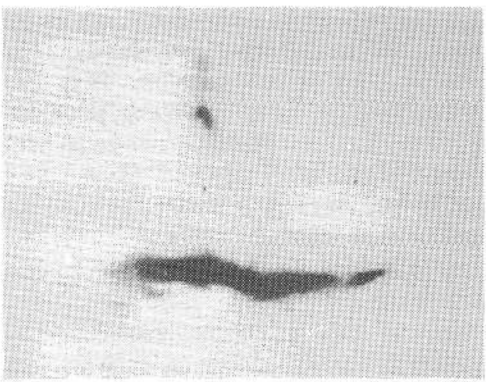
FIGURE 15
Photo taken 300 nseconds later than the **I** peak. Note that neutrons are being produced and the pinch has vanished completely. The bright regions show vortex filament pairs combining in both halos (inside and outside the center conductor) as the circles travel radially outward. The "circles" are the intersection of a spherically shaped shock wave with the current sheath.

Measurement of intensity of image as a function of angle enables us to calculate that it is more of an electron beam along the axis than a thermal ensemble that is producing the x-rays. *(60, 64)* The x-rays are apparently coming from a deuterium plasma of high purity in this hollow-center-conductor machine: An addition of 0.5 per cent argon gas (by pressure) to the filling of 8 Torr of D_2 increases the intensity of the radiation in the x-ray image by at least a factor of 10. From the absolute intensity of the x-ray images and the x-ray spectrum measured with several B_e filters of varying thickness a dominant electron energy of 8 Kev can be assigned. *(60, 64)*

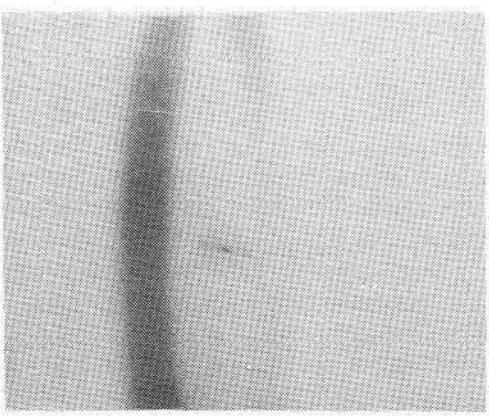
The flashing time of the x-rays from the individual sources is recorded with NE 102 scintillator, 931A PM tube and a 7704 Techtronics scope to be 5 ns, FWHM, but this is the FWHM of the instrumentation. The corresponding pulse for the neutrons is ~5 ns, FWHM, when the scintillator is only 30 cm from the focus. The flashing time of the x-rays as recorded with the 931A PM tube without the scintillator is ~3.5 ns, FWHM, which is



45°



45°



80°

FIGURE 16

a

X-ray pinhole (75μm diameter) photo taken at 45°. Be absorber 50 μm ($\epsilon \geq$ 2Kev). The printing of the photo is light enough to show an intense localized source which is embedded in the broad source of softer x-rays on the electrode axis.

b

Same as 16a but darker printing to show details of boundary of the broad x-ray source along electrode axis. Note two localized sources with apple-core profile below broad source.

c

Same shot with x-ray pinhole photo at 80°. Pinhole diameter is 13μm in 20μm of Ni. Absorber is 50μm of Be ($\epsilon \geq$ 2Kev). Note very small localized source ($\sim$50μm in diameter), and the leakage of the 20-μm-thick Ni foil which was placed in a 1.6 mm-diameter hole in Cu. The broad, vertical x-ray source outlines vertical portion of center electrode. The small divisions in the printed scale spaced by 1.7mm. The filling is 8 Torr of D_2 with 1% Argon. The localized source in photograph at 45° is the same localized source seen in photograph at 80°.

again the FWHM of the instrumentation. From the shape of the pulses we have concluded that the flashing time of the individual sources is $\leqq 1$ ns and that as many as five of these sources can flash so close together in time that our instrumentation cannot fully resolve the composite pulse into its components: The small bumps on the pulse can only suggest that there are components. From the absolute intensity of the x-ray image and the flashing time one computes that the peak electron density in the current channel of the source is $10^{20} - 10^{21}$, that the current density can go to 10^{13} amperes cm^{-2}, the total current in the channel to 10^7 amperes, and the magnetic field, (either the local B_z or B_θ) to 6×10^8 G. The current in the channel can legitimately be far above the Alfven limit because of the large local B_z and the fact that the plasma is highly collisional.

When the choking of the current in the channel causes an accelerating field to be produced by the resulting dB/dt, it is estimated that this field goes as high as 10^8 volts/cm. It is this field which gives the electrons energies up to $\sim$2 Mev to produce x-rays, and deuteron energies in the 10 to 1000 kev range to produce neutrons, with energies all the way up to 5 Mev. This highly concentrated plasma in the current channel is called a plasma nodule.

With the small $\sim$5-KJ, 600-Ka plasma focus machine operating at Stevens secondary nuclear fusion reactions have been observed *(60,65)*; that is, the 14 Mev neutrons from the D-T reaction have been observed by time of flight when only D_2 was used in the filling. In a typical shot yielding 5×10^8 D-D neutrons about 10^4 D-T neutrons will be observed in a short (<10 ns) pulse. The only plausible interpretation is that enough T was produced and trapped in the nodule for the D-T reaction to proceed at a detectable rate.

The oscilloscope traces of an uncollimated neutron pulse show a sharp peak and then an exponential tail with a half life of about 50 ns. *(66)* If the neutron pulse is taken at 90° to the machine axis with a 1 cm $\times$ 1 cm aperture in a paraffin collimator, the tail is chopped off. The interpretation is clear and straightforward: The sharp peak is the neutron production in the concentrated dense nodule where $n_e \rightarrow 10^{21}\,cm^{-3}$ and the tail is produced by a deuteron beam emanating from the nodule and coursing through the cold background filling gas where $n_e \sim 10^{18}\,cm^{-3}$. Evidence of this deuteron beam and its neutron production has already been reported by the Darmstadt *(67)*, Limeil *(32)*, and LLL plasma focus groups. *(68)*

The Stevens measurements show that for this small focus machine **at least half** the neutrons are produced in the nodule where the particle orbits are highly influenced by the large magnetic fields and where the electron energies are of the order of **10 kev!** In the nodule, loss of deuterons by charge exchange is no problem: "burnout" of any residual neutrals is complete. This plasma nodule is not such a bad target for the high energy deuterons which are constantly being accelerated within it. It will be several years and millions of dollars before the two component Tokamak at PPPL has a target with electrons of such high energy. One may note that the plasma nodule is uncontaminated with metal ions and that the high electric fields for accelerating the deuterons (and also the electrons) are beneficently produced by nature *in situ* without having to petition ORNL and LBL and LLL to develop and build neutral beam accelerators for injecting the high-energy deuterons. One may further note that the force-free 600 MG magnetic field that provides both the energy source for the acceleration and the magnetic confinement is provided by nature without the necessity of superconducting coils or copper coils which can be damaged by the neutron flux.

If one were to reconstruct the neutron pulse by eliminating the instrumental broadening of the pulse, the sharp peak would be 1 n sec or less in FWHM, 30 times or more as high as the start of the exponential tail, which has a decay half-life of 50 ns.

Ardent proponents of the Tokamak like the idea of a "driven" reactor at high magnetic fields because the power density can be high. In the plasma nodules of even this small plasma focus at Stevens the input power within a single nodule is 10^{10} watts and the power input density is $\sim 10^{16}$ watts $cm/^{3} =$ 10^4 terrawatts/cm^3. And this is for a plasma focus whose $n\tau = 10^{21} \times 10^{-9} = 10^{12}$ which is 10^{-2} short of the Lawson $n\tau = 10^{14}$. For a "breakeven" plasma focus, the power input and power output per nodule and power densities will presumably be much larger.

Space-Time Resolution

Over a period of about 25 years there have been quite a number of hypotheses advanced to describe the mechanism and mode for energizing and directing the deuterons in the pinch effect and the plasma focus (the "moving boiler," *(42)* the charged plasma capacitor plate, $m = 0$ instability, turbulent heating). There have been magnificent experimental techniques employed — curved crystal x-ray spectroscopy, time-resolved interferometry for electron density measurements, measurement of electron density and temperature and ion temperature by Thomson scattering of laser light. The Culham Laboratory and the Limeil group have been particularly skillful with these techniques that are considerably beyond the modest resources available to the small plasma focus group at Stevens. There have been highly advanced computer simulations of the current sheath dynamics by Potter, Los Alamos, and the Soviets. In fact there is the whole early history of the pinch effect in the USSR which I hope the Soviets will some day write, and there are the many contributions which their people have made to the plasma focus development. The reader might ask "Why is the author, who represents such a small plasma focus group, in such a sea of international talent writing this article."

The author would reply that the key to studying properly the plasma focus is in space-time resolution of the instrumentation. The Stevens spatial resolution in x-ray pinhole photography has been a factor of 10 better than any of the spacial techniques employed elsewhere. The Stevens neutron collimation gives the best (as far as we know) neutron spacial resolution. The Stevens scintillator and PM analysis of x-ray and neutron pulses has yielded the best time resolution. The key to understanding is recognizing that the essence of the plasma focus lies in its fine structure. This sentiment is also expressed by the French plasma focus group at Limeil. *(69)* To describe the plasma focus without knowledge of its fine structure would be like trying to describe the nature of infectious and contagious disease without admitting the Pasteur results concerning the role of microbes, or to describe the behavior of gases without recognizing the Dalton hypothesis of the existence of atoms or molecules.

In the study of plasma physics the long-overdue recognition of the arrival at the "Pasteur" or "Dalton" stage is here at hand: Theoreticians now take quite seriously the possibility of discrete entities like solitons and cavitons that can be whipped up out of an otherwise amorphous soup. But the most spectacular of plasma entities, the vortices, have long been experimentally staring us in the face, starting with the bouncing of plasmoids off each other (like billiard balls) in 1955 *(70-74)*, continuing with the fountain pinch *(27)*, the filaments of Kvartskava *(24)*, the plasmoids of Wells *(28)*, the vortex filaments in the plasma focus current sheath. And now the sharpest of all plasma boundaries (as far as the author is aware) can be shown in the plasma nodule of the plasma focus: An electron density profile across the channel of a plasma nodule has been made by performing an Abel inversion procedure on the microdensitometer scan of an x-ray pinhole camera image. This density profile *(60)* is shown in Figure 17 along with a computed "Bennett" profile. *(2)* It must be remembered that the plasma nodule channel contains, ac-

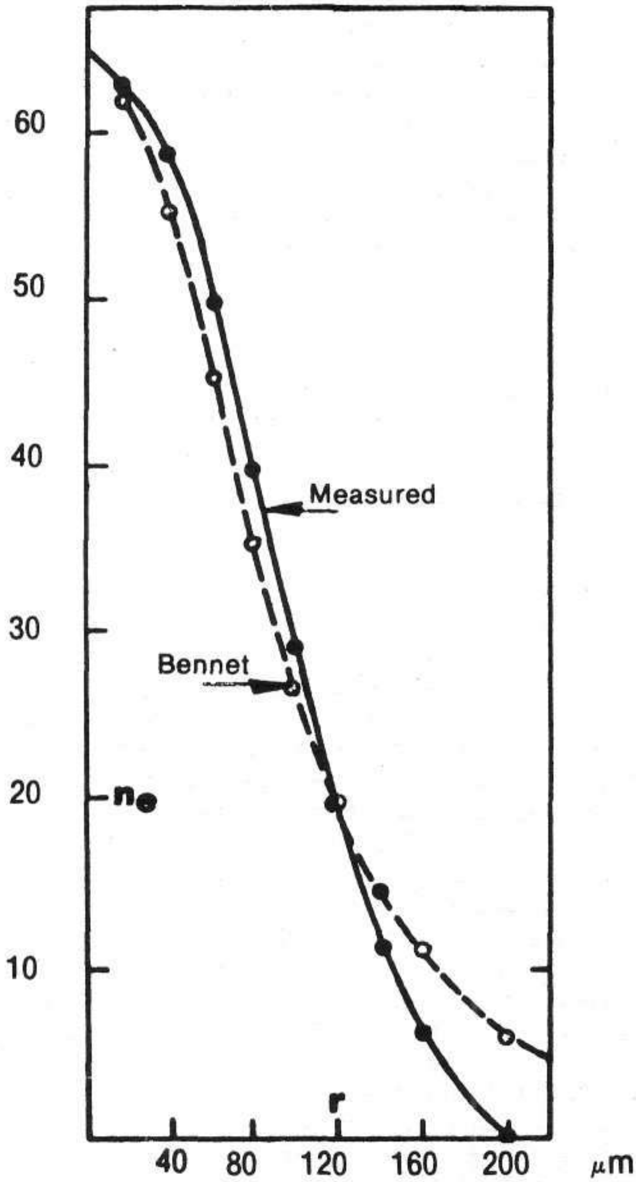


FIGURE 17

Plot of electron density n_e versus distance r from the source axis (which is taken to correspond to point of peak intensity). This radial profile is derived by using a best fit with Laguerre and Hermite polynomials (a method equivalent to Abel inversion but more general) of microdensitometer readings on a localized x-ray source. Plotted also for comparison is a Bennett profile $n_e = n_o(1+ bn_o r^2)^{-2}$; the constant b is obtained by a best-fit of emission coefficient within a distance r $\lesssim$ 0.2 mm from source axis. Vertical scale n_e is in arbitrary units.

cording to the best estimates, both a B_z and a $B\theta$ of magnitude up to ~ 600 MG, and vorticity and mass velocity and current vastly exceeding the Alfven limit, and that it lasts approximately ~ 1n sec. One should, therefore, not expect the measured density profile of the nodule (a paramagnetic vortex) and the Bennett profile to agree: The Bennett density profile approaches zero asymptotically. The measured boundaries of the diamagnetic vortex (Figures 8 and 9) are also very sharp.

It appears that the radius of the plasma vortex filament in the current sheath and the radius of the channel of the plasma nodule are the nearest experimental realities to the Rosenbluth-Ferraro theoretical sheath thickness c/ω_p.

Perhaps the ultimate in techniques for observing the fine structure of plasma has been the "plasma scope" in the hands of Joseph Zorskie at Stevens in his doctoral thesis. *(75)* Zorskie fired a burst of plasma from a small button plasma gun across a homogeneous magnetic field. At a position along the field about 20 cm from the gun there is positioned a fine metallic screen and behind that a thin aluminum coating attached to a disk of plastic scintillator. The holes in the screen admit a small fraction of the plasma, and a 20 Kv pulse, 0.1μ sec long is applied between the screen and aluminum coating so that the electrons in the plasma are accelerated to 20 Kev, penetrate the foil, and produce a scintillation light pattern, which is photographed by a camera focused on the boundary between the plastic disk and the thin aluminum coating. The photographs so obtained show the density distribution of the plasma at the position of the screen at the time the voltage pulse is applied. Figures 18 and 19 taken by Zorskie show that for low magnetic fields the plasma expands with many small diameter filaments that appear, almost like the mycleum of fungi, to produce a kind of fuzz. These small diameter filaments are also, very likely, vortex filaments akin to those observed in the current sheath of the plasma focus. One must recognize that whenever a plasma is accelerated or decelerated by a magnetic field, vortex filament formation is to be expected.

On the grounds of the predication of the importance of the plasma fine structure the author is including these experimental results in the history of the pinch effect. While one would certainly not call these results the last chapter of the pinch, they might possibly be called the next to the last chapter. The space-time resolution of the instrumentation needs some improvement before one tackles the last chapter, but at any rate at this point one can hypothesize on the origin and nature of the plasma nodule.

In the pinch phase of the plasma focus when the left-handed and right-handed vortex filament pairs in the current sheath are beginning to consume each other and destroy these ingeniously constructed current-conducting paths, it is quite conceivable that a few unpaired filaments survive, unscathed by these consuming suicide pacts. These few unpaired filaments are now obliged to carry all the current that was previously carried by the many and their local B_θ's thus vastly exceed their local B_z's and each filament coils into a toroidal solenoid which soon connects itself up to itself at the two ends of the filament. This toroidal solenoid wound up with a force-free "wire" carrying current density, vorticity, magnetic field, and mass velocity is depicted in Figure 20. *(76, 77)* When the x-ray pinhole technique improves one can draw a more accurate Figure 20. The central channel of this solenoid becomes the plasma nodule with diameter $\sim 10\mu$m. During the formation of this nodule the electron temperature remains that of the current-sheath vortex filament ($\sim$20ev, the ion energy $\sim$50ev. The channel is protected from madly radiating its energy as synchrotron radiation as long as the plasma frequency exceeds the synchrotron frequency and as long as the electrons have low energy. As the solenoid is formed, turn upon turn, but in a matter of $\sim$5 – 30 ns, the magnetic fields along the channel and around the channel increase and finally the synchrotron frequency exceeds the plasma frequency. The electrons in the channel radiate synchrotron radiation, and as they lose energy the current in the channel starts to be choked. The magnetic field responds by generating large electric fields to sustain the current, and electrons and deuterons are accelerated. It is also quite possible that at the ends of the nodules with their mirror-type magnetic fields there is generated the electric field associated with Raudorf's electronic ram. *(78)* The plasma nodule is a natural plasma betatron which exceeds the wildest dreams of Budker, Bennett, Finkelstein, Rogers, and others who worked at designing and building plasma betatrons in the late 1950's. *(79)*.

An interesting aside is that the neutron and x-ray pulses do not come at the moment of the peak in the $\dot{I}$ trace (I is the current in the machine) as they were assumed to do by the entire profession for about 13 years. The neutron and x-ray pulses come 20-50 n sec after the peak of the $\dot{I}$ trace. This fact was first established by the careful measurements of Lawrence Grunberger, a graduate student at Stevens, and the results were reported by Vittorio Nardi at the Rome meeting of the

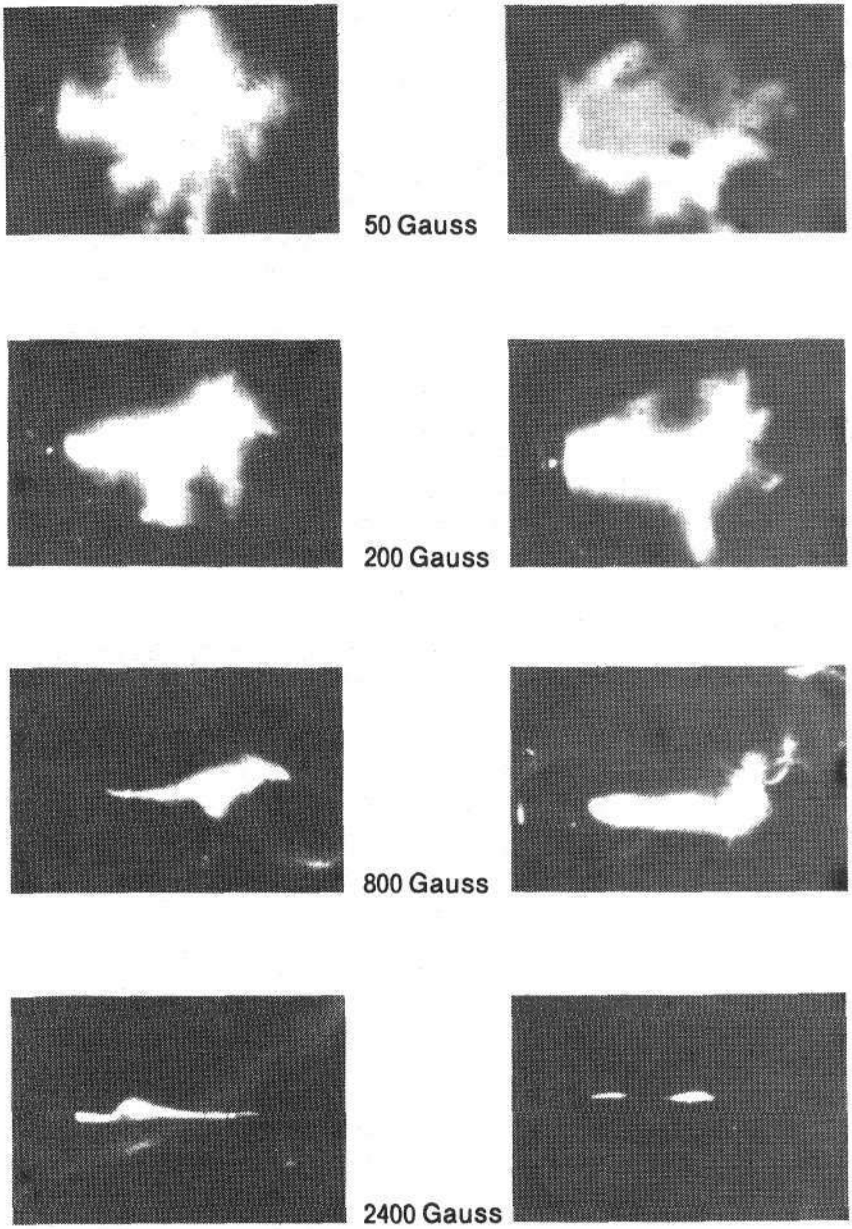
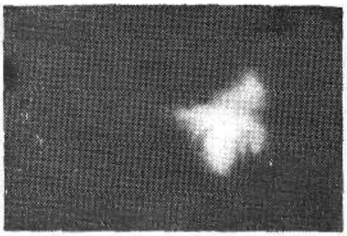


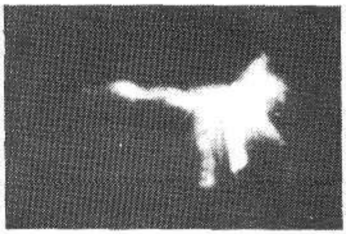
FIGURE 18

Plasma camera photographs of copper plasma injected from the right taken after 2.4 microseconds in various magnetic fields. The left and right columns contain photos of opposing and aiding gun polarities respectively. Between the columns are depicted plasma y dimensions (h) calculated from the assumption B_o h is constant.

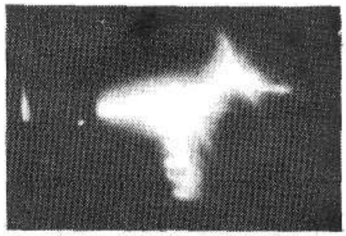


1.0

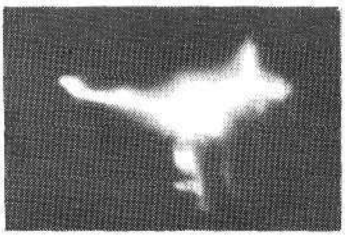
1.6



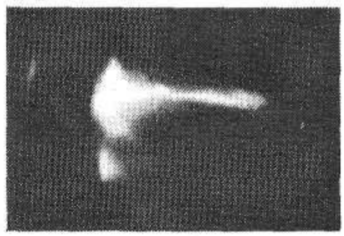
2.2



2.4



3.2



4.9

400 Gauss

FIGURE 19

Plasma camera photographs at .1 microsecond exposure of the electron density distribution of a copper plasma taken at various times after the gun fires. Plasma, injected from the right, is seen at times of 1.0, 1.6, 2.2, 2.4, 3.2, and 4.9 microseconds as it moves across a 400 gauss field. The protuberances extend in the—VXB direction, downward here. The gun is in opposing polarity.

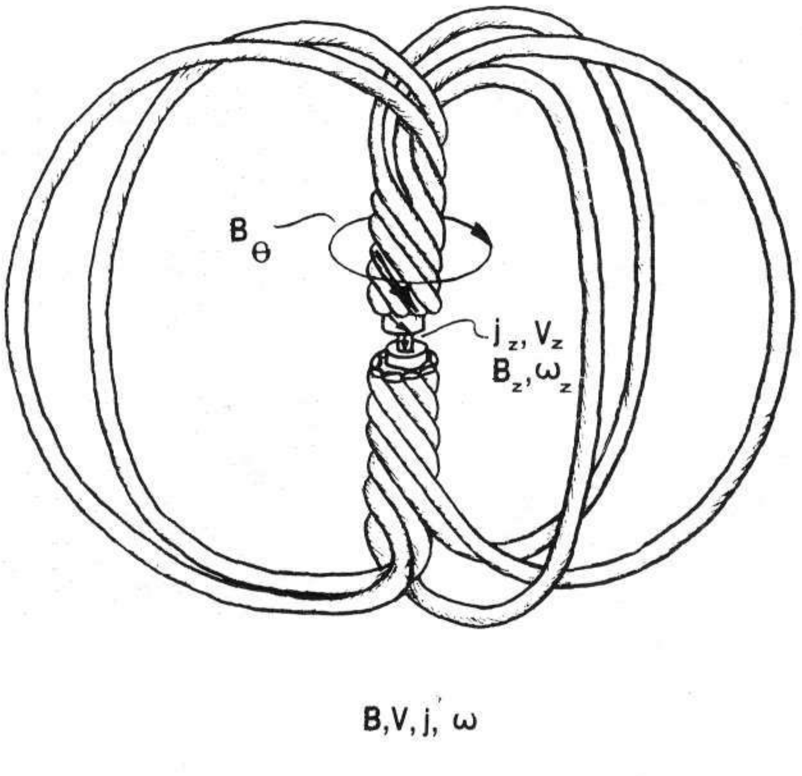


FIGURE 20

Diagram of a plasma nodule, a toroidal solenoid wound with a force-free wire carrying current density j, vorticity ω, magnetic field B, and mass velocity V.

European Fusion Conference in 1970. *(80)* There is also an $\dot{I}$ peak (or several small peaks) associated with the vortex filament destruction in the halo when a second group of neutron and x-ray pulses come about 250 n sec after those which come from the axial region.

The skeptics of the CTR profession might now interject the practical question: "How could the plasma focus possibly be considered as a competitor in the CTR magnetic confinement league?" A necessary (but not sufficient) portion of that answer is found in the recent Stevens results showing that at least half of the neutrons come from the high-density, high-electron-energy, high-magnetic-field region in the nodule, even in a small 5kJ plasma focus. Stevens has not had the resources to study the nodule process as the machine's peak current is increased. Consequently one can say very little as yet about the anatomy of the neutron-production scaling laws for the plasma focus. Figure 21 shows an empirical scaling of neutron production versus peak current (as best it could be determined) for the various important plasma focus machines thus operated and reported. *(81)* Note that the empirical scaling is over a range of almost 5 orders of magnitude in neutron production and that the I_p^5 law holds over that range. Obviously one should design a relatively small plasma focus machine for high voltages to achieve a high I_p. A program of design and operation of high I_p machines should be instituted. In the arguments the author has advanced, he has tried to prove that it is legitimate for the ERDA CTR magnetic confinement program to pay for such a program. Figure 21, which is taken from an LLL design study, indicates that a "breakeven" machine of the type designed will occur at about 4MJ and 16Ma.

The extrapolation in neutron production from Mather's last 400 KJ machine to the breakeven machine represents the same range ($\sim$5 orders of magnitude) as the empirical I_p scaling has thus far covered. The extrapolation in peak current is only by a factor of 8.

With artful design techniques (small size, low inductance, high voltage) it should be possible to make an $I_p = 16$ Ma machine at considerably less than 4 MJ. The cost would be about $5 million and the time about three years.

Greatly anticipated by the profession are the neutron yields of the 1 MJ plasma focus now just going into operation at Frascati. The LLL new 1 MJ plasma focus has been operating with one-quarter of its capacitor bank and at 25 kv (instead of 40 kv) at about 1.3 MA, and its neutron yields fall nicely on the I_p^5 line of Figure 21. There have been theoretical reasons advanced for an I_p^5 neutron scaling law. *(82)* The author believes that the calculations are based on a model for the neutron producing

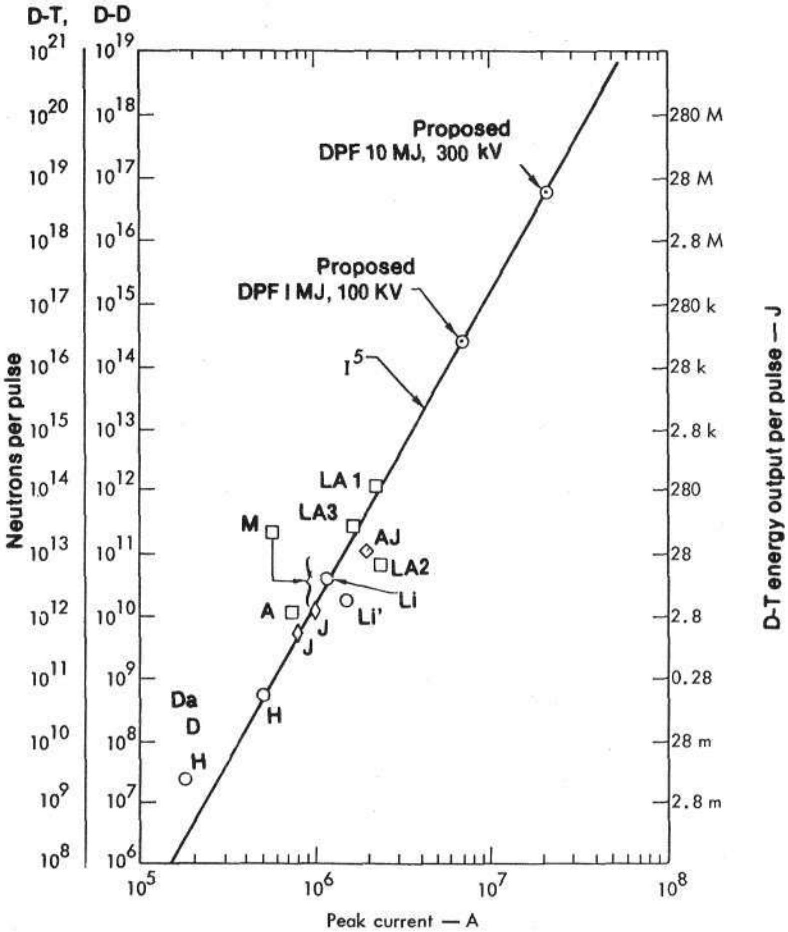


FIGURE 21

Global empirical scaling of the world's plasma focus machines showing neutron yield and energy output versus peak current in the machine.

mechanism that is incorrect in detail but is perhaps valid for the gross energetics of neutron yields.

The intensity of the electron beams and deuteron beams that emerge from the plasma nodule are phenomenally high and are being considered for pellet implosion and heating. *(83-85)* The deuteron beam at the nodule is of the order of 10^5 amperes and 10^9 amperes per cm^2.

For at least two years J.S. Luce, R. Gullickson, B. Freeman, O. Zucker, and H. Sahlin at LLL have found strong empirical evidence for the existence of vortex filaments in relativistic electron beams. By exploiting the behavior of these filaments, Luce has been able to improve markedly his collective acceleration of protons to 40 Mev by electron beams. The LLL plasma focus program under Luce's direction has used the proton beam from a hydrogen-filling of its plasma focus to produce 10^6 neutrons from a target of a small deuterated polyethylene pellet.

At the IEEE plasma physics meeting at Austin, June 1976, researchers on relativistic electron beams at both NRL and Sandia reported enthusiastically evidence of "filaments" in their relativistic pinches. At the 1971 APS Plasma Physics Division Meeting in Madison, Wisconsin the author remembers sitting through an immense rash of Sandia papers on relativistic electron beams, and one paper showed clear evidence of pairs of plasma vortex filaments. The author pointed this out to the Sandia physicists, but apparently the remark at that time had no effect. The author also listened in October 1975 to an invited paper by a Sandia physicist on certain aspects of their electron beam program. When asked whether they observed evidence of filaments, the reply was negative. Now at last (years and millions of dollars later) it is gratifying to see that people from large, financially favored laboratories have decided to "join the club" and recognize that after all there may be something to this Pasteur era of plasma physics, even in the field of relativistic pinches. They are a bit too late, however, to qualify for charter membership.

On the other hand, the author is pleased to acknowledge the work of M. Cowan at Sandia who observed filaments in current sheaths several years ago. The author also remembers a paper given by the Limeil group in Miami in 1968. Their Schlieren photos, examined carefully by the author, clearly showed evidence (which they did not report at that time) of filaments in their plasma focus. The author was also able to delineate (around 1967) the presence of closely spaced filaments (which were not reported) in the image converter pictures of the Los Alamos plasma-focus current sheath.

When the author went to work at LLL in 1954, he petitioned for permission to use a Langmuir probe to observe any possible evidence of fluctuation of ion density in their CTR mirror compression machine. After some delay, he was granted this permission for a few hours, and he placed a probe in the machine. The results showed sizable fluctuations in ion density and electric field. In retrospect, the author now recognizes the signature of these fluctuations as the result of diamagnetic plasma vortices moving around through the magnetic field: The plasma vortex was being unconsciously discovered at that moment. The scientist in charge of the mirror machine declined to attribute any significance to the results and chose to ignore them.

The Unfinished Saga of the Pinch Effect

In the matter of large plasma focus machines that produce large numbers of neutrons, the drama has been something like a great classic automobile race: Joe Mather, the winner of many races, driving the most powerful operating machine to date (his 700 KJ), is retired early in the last race at a pit stop because his government sponsoring agency declined to pump him any more gas. The most powerful machine built thus far, the Frascati 1 MJ, is still in the shop. Filippov, who hails from Tokamak country, is obliged to visit the Frascati shop frequently in order to be near a powerful machine. Bennett, after superb conceptual performances in early races, turned in a remarkable conceptual lap in the matter of relativistic pinches before he was retired because of age. John Luce operating the LLL 1 MJ machine on only one-quarter of its cylinders is turning in some superlative laps where he extracts 75 per cent of the machine's energy into the pinch. The officials are repeatedly trying to flag him down and retire him from the race because of age, but he keeps on lap after lap, scrounging gas from other people's tanks when need be. Luce recently on other days has turned in stellar laps in the races involving relativistic electron beam pinches that are used for neutron production and collective acceleration of positive ions where he is world champion. He does most of the work in the pit stops by himself. *(86)* These are recent accomplishments by a man who 23 years ago was the inventor and developer of the DCX 1 program at Oak Ridge. A comparable span of accomplishments in the skiing sports world, for example, would be the achievement of world championships in both cross-country and alpine categories in one lifetime.

It is somewhat doubtful that these several Moseses of the pinch-effect world will live to set foot on the promised land of a "breakeven" plasma focus machine. Since ERDA (formerly the AEC) has declined to sponsor plasma focus research for the last 15 years, and since the plasma focus has no friend in court in the FPCC, the Washington CTR office, its consultants, or the upper CTR bureaucratic muscle of the national laboratories, it is perhaps an idle dream to think of designing and building a breakeven plasma focus machine.

Though researchers at Stevens may have envied the plush funding and resources enjoyed by their Tokamak, stellorator, and mirror brothers, they would never for a minute have given up the once-in-a-lifetime exhilaration of discovering and studying the plasma vortex filament. Even if the USSR had provided for Lev Arzimovitch, the super salesman of the Tokamak, the ultimate sanctification of laying him out along side of Lenin in the tomb at Red Square, they would never for one moment have traded their romance with the plasma vortex filament for all the prestigious flush and financial salvation of Tokamak fever. Indeed, if the right physicist with the right attitude and proper instrumentation takes a really careful look at the Tokamak he will probably find plasma vortex filaments there, where they may well be playing a significant role in neutron production. It took 14 years before the vortex filaments were discovered to be significant in the pinch effect, and 24 years before the profession at large began to take them seriously in the pinch effect. The Tokamak is not yet 24 years old.

In the fall of 1975, Robert E. Hirsch, then the director of ERDA's CTR Division, addressed scientists and engineers at Los Alamos, proclaiming that the research phase of the U.S. CTR program was over, that from then on it would all be technological development, and that irrational criticism of the Tokamak program would not be tolerated. These remarks bring to mind an answer given by an elderly, laurel-rich A. A. Michelson to the question "Where lies the future of physics?" Michelson replied, "In the last decimal place." Although Michelson had lived and worked at the threshold of the greatest era in physics, his imagination was unable to project itself into this era which would witness the developments of quantum mechanics, nuclear physics, high energy physics, solid state, general relativity, and so forth. If Robert Hirsch really and for keeps means what he said at Los Alamos, he is choosing to ignore the fact that plasma physics is at the threshold of the Pasteur or Dalton era. But history perhaps will not permit him entirely to escape that fact.

The history of the pinch effect has amply demonstrated some of the great complexities inherent in plasma physics. These complexities of which one was not apprised in advance by the celebrated oracles at Moscow, Princeton, LLL, LASL, Culham, Paris, and Garching. These complexities represent potential hidden navigational hazards, or possibly favorable currents, for all CTR craft and sailors, including the Joint Congressional Committee on Atomic Energy and bureaucrats on the bridge. These complexities could delay a voyage, damage a craft, sink a ship, or make an otherwise impossible voyage possible. The understanding of these complexities of nature will come primarily through patient research, not through Washington-orchestrated technological development. All CTR sailors, take notice!

Postscript

from the IAEA Conference on Controlled Nuclear Fusion and Plasma Physics, October 1976, Berchtesgaden, West Germany

It is indeed true that filaments (or islands) are now being observed in the Tokamak machines, and even the concept of vorticity was introduced in a paper by Webb of the United Kingdom who theoretically modeled the formation of the filaments. In papers, written principally by the Soviets and the French, on the analysis of the behavior of these filaments in producing disruptive instabilities, it was stated that the coming together of an $m=1$ and an $m=2$ filament brought about a reconnection of magnetic field lines that generated a sudden increase in resistance to the flow of toroidal current in the Tokamak with an accompanying emission of x-rays and r-f.

Boris Kadomtsev in his analysis likened the process to the solar flare phenomenon and posed again the perennial obstacle in the understanding of how two juxtaposed plasma filaments carrying current in the same direction, where there is a conducting plasma cushion between them, can come together so fast. In other words, how can they reconnect their magnetic fields so rapidly when there is a fairly highly conducting plasma in between them that will slow down the rate of diffusion of magnetic fields through the plasma. It is as if this cushion of conducting plasma suddenly experiences locally an "anomalous resistivity" much as the pinch-effect plasma and the plasma-conducting high current do in "turbulent heating."

The answer to this perennial riddle can be found in recognizing that "equilibrium plasmas" are more a theoretical convenience than a reality, and that 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 currents always parallel to a local magnetic field B.

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 their magnetic energy ends up in particle energy; "anomalously high resistivity" suddenly has appeared locally. If this process occurs in a region between two large filaments, the large filaments quickly come together as the forces, and motion between the two large filaments brings about a propagating region of destruction of the small vortex filaments between them.

This process is much more rapid than classical diffusion of magnetic fields through a plasma whose resistivity is governed by the Spitzer formula. It was recognized ten years ago in plasma focus research that the high back emf that produced the high di/dt at the time of the pinch was due more to the destruction of vortex filaments than to the dL/dt because of the rapid constriction of the column, and that this destruction took the form of high resistance as the local magnetic field lines of the vortex filaments were reconnected, and that this is the solar flare process.

The author hopes that the study of this basic process of filament disruption by the Tokamak people not only will again show plasma physicists our kinship with the cosmos (the solar flare process) but also will remind us of the mutual brotherhood of the Tokamak and the plasma focus, and that one brother should not neglect or ignore another.

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ABBREVIATIONS

APS — American Physical Society
AEIRL — Associated Electrical Industries' Research Laboratory
CTR — Controlled Thermonuclear Fusion Research
ERDA — Energy Research and Development Administration
FPCC — Fusion Power Coordinating Committee
FWHM — Full width half maximum
IAEA — International Atomic Energy Agency
IEEE — Institute of Electronic and Electrical Engineers
LASL — Los Alamos Scientific Laboratory
LBL — Lawrence Berkeley Laboratory
LLL — Lawrence Livermore Laboratory
NRL — Naval Research Laboratory
ORNL — Oak Ridge National Laboratory
PM — Photo multiplier
PPPL — Princeton Plasma Physics Laboratory
SCEPTRE — Toroidal apparatus at Harwell, which preceded ZETA
USAEC — U.S. Atomic Energy Commission
ZETA — Toroidal apparatus at Harwell and Culham

About the Author

Winston H. Bostick has been George Meade Bond Professor of Physics at Stevens Institute of Technology since 1956. During this 20-year period, Bostick headed the Stevens Department of Physics for 12 years and he spent two years teaching and working abroad. In 1970 he held a UNESCO visiting professorship at the University of Buenos Aires, Argentina where he helped set up an experimental plasma physics program, and in 1961, Bostick worked at Fontenay-aux-Roses in France and Culham Laboratory in England under a National Science Foundation Senior Postdoctoral Research Fellowship.

From 1948 until a two-year leave of absence spent at Lawrence Livermore Laboratory in 1954-56, Bostick was on the faculty of the Physics Department at Tufts University. At Tufts he worked with M. Levine and L. Combes on magnetized plasma research, including the pinch effect and ambipolar diffusion across magnetic fields. At the Lawrence Livermore Laboratory, Bostick investigated the properties of plasma projected across magnetic fields and demonstrated that the plasma in the magnetic field could form well-defined integral entities called plasmoids. Later at Stevens his research work with V. Nardi and W. Prior showed that the plasmoids are made up of plasma vortex filaments and that the formation of plasma vortex filaments is a natural and almost universally recurring phenomena in plasmas — in both astrophysical and laboratory plasmas.

During World War II, Bostick was a staff member at the Radiation Laboratory of the Massachusetts Institute of Technology, and he contributed four chapters on pulse transformers to MIT's technical series volume, *Pulse Generators*. After the war Bostick worked briefly at MIT's Research Laboratory of Electronics on his invention, "the fizz chamber," an early attempt to make and operate a cyclohexane-filled bubble chamber. When MIT's J.C. Slater needed manpower for the design and construction of the MIT microwave linear accelerator, Bostick was transferred to that project until 1948 when he accepted a position at Tufts.

Bostick holds a BS (1938, Phi Beta Kappa) and a PhD in physics (1941) from the University of Chicago where he completed his thesis under the direction of A.H. Compton and M. Schein.

Bostick has written more than 90 scientific papers, mostly on plasma physics, including an article for *Scientific American* and contributions to *Colliers Encyclopedia* and *Encyclopedia Americana*. In 1961, Bostick won first prize in the Gravity Foundation Research essay contest with a piece entitled "The Gravitationally Stabilized Hydromagnetic Model of the Elementary Particle."

In 1966, Bostick was a Democratic primary candidate for the U.S. House of Representatives for New Jersey's 5th Congressional District, and two years later he was a McCarthy-pledged delegate from New Jersey to the Democratic National Convention in Chicago. He is a Fellow of the American Physical Society, and a member of Sigma Xi and the American Association of University Professors.