to "bend," without stretching or tearing, the helicoid into the catenoid. This process of bending a helicoid into a catenoid, or vice versa, is essentially the same as bending a flat sheet of paper to form a cylinder. The difference is that the helicoid is both bent and twisted to become the catenoid.

The transformation by bending of the catenoid into a helicoid is shown in the rest of Figure 3. This transformation demonstrates one essential quality of Gaussian surface curvature: The surface curvature is intrinsic to the surface and remains the same no matter how we bend the surface.

Negative curvature space

Lyndon H. LaRouche, Jr. suggests in his 1989 book *In Defense of Common Sense* that the Beltrami negative curvature approach to the physical geometry of space-time provides an important advance beyond that made by Eugenio Beltrami's close collaborator Bernhard Riemann. The above geometrical constructions showing the connection between spiral cylindrical action, as characterized by Beltrami plasma vortices and minimal surfaces, while admittedly much simplified, do appear to provide a useful introduction to the broader aspects of the Beltrami approach. LaRouche suggests that Beltrami negative curvature will be crucial for developing insights into the way the nucleus and subatomic particles are created and work.

LaRouche's *In Defense of Common Sense* discusses the connection between his concept of negentropy and Beltrami negative curvature:

"Earlier, we considered one implication of [Cardinal Nicolaus of] Cusa's Maximum Minimum Principle: *the minimal action required to generate the relatively maximum work (e.g. "volume") accomplished*. Now, consider the complementary notion: *The minimum work required to generate the relatively maximum action*. Let us associate the first with the obvious choice of term, *positive curvature*. Let us associate positive curvature with the term *weak forces*, and negative curvature with *strong forces*. Let us examine this array, first, in light of the Riemann Surface Function, and then, the prospect for constructing the more adequate *Riemann-Beltrami* Surface Function. . . .

"Yet, those various measures of *negentropy* define processes which are *bounded by* negentropy, without representing the negentropy itself. Once we shift our focus to the causal sequence of alternating *weak* and *strong* 'forces,' the intelligibility of negentropy becomes a distinct geometrical idea; the negentropic process is then represented intelligibly as *a self-bounded process*."

As the work of Professors Dan Wells and Winston Bostick has shown, this Beltrami approach is most fruitful for constructing a universal mathematical physics which provides a coherent overview ranging over particle, atomic, plasma and astro-physics, and over the geometries of what is otherwise described today as the weak and strong forces of matter.

The pinch effect revisited, part 3

by Winston H. Bostick

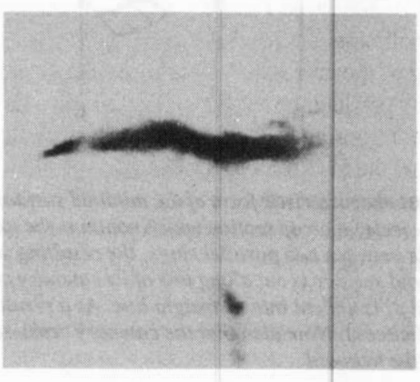
In Part 2 of Dr. Winston Bostick's work, which first appeared in the March 1977 inaugural issue of the International Journal of Fusion Energy, *he discussed the discovery of plasma vortex filaments by researchers in controlled thermonuclear fusion research (CTR). Bostick showed how what appeared to be an anomaly or instability in the existence of these vortex filaments, was actually quite lawful.*

In the beginning of his history of this aspect of fusion research, Bostick described the pinch effect as "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."

An X-ray pinhole photo (**Figure 16**)* with a 50 micron Be screen (>2 kev) shows multiple intense spots imbedded in a

FIGURE 16

X-ray pinhole (75 μm diameter) photo taken at 45°



Be absorber 50 μm (ε⩾2 kev). 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.

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 micron) to (50 micron) delineate the shape (like a bow tie or concave spool or apple core) and minimum dimensions of these images (50 micron diameter, 400 microns 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.

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. The X-rays are apparently coming from a deuterium plasma of high purity in this hollow-center-conductor machine: An addition of 0.5% argon gas (by pressure) to the filling of 8 Torr of deuterium 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 Be filters of varying thickness a dominant electron energy of 8 kev can be assigned.

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 5 nanoseconds, FWHM, but this is the FWHM of the instrumentation. The corresponding pulse for the neutrons is ~5 nanoseconds, 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 nanoseconds, FWHM, which is again the FWHM of the instrumentation. From the shape of the pulses we have concluded that the flashing time of the individual sources is <1 nanosecond 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 per sq cm, 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 Gauss. 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 per cm. It is this field which gives the electrons energies up to ~2 Mev to produce X-rays, and deuteron energies in the 10 to 1,000 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 ~5 kilojoule, 600 kiloamp plasma focus machine operating at Stevens, secondary nuclear fusion reactions have been observed; that is, the 14 Mev neutrons from the deuterium-tritium (D-T) reaction have been observed by time of flight when only deuterium 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 nanosecond) 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 nanoseconds. If the neutron pulse is taken at 90 degrees to the machine axis with a 1 cm×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 $n_e \rightarrow 10^{21}$ per cubic centimeter and the tail is produced by a deuteron beam emanating from the nodule and coursing through the cold background filling gas where $n_e \sim 10^{18}$ per cubic centimeter. Evidence of this deuteron beam and its neutron production has already been reported by the Darmstadt, Limeil, and Lawrence Livermore Laboratory plasma focus groups.

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 Princeton Plasma Physics Laboratory 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 Oak Ridge National Laboratory and Lawrence Berkeley Laboratory and Lawrence Livermore Laboratory to develop and build neutral beam accelerators for injecting the high-energy deuterons. One may further note that the force-free 600 MegaGauss magnetic field that provides both the energy source for 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 nanosecond 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 nanoseconds.

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 per cubic cm, or about 10,000 terawatts per cubic cm. 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," 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 at Los Alamos and by the Soviets. In fact there is the whole early history of the pinch effect in the U.S.S.R. 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?"

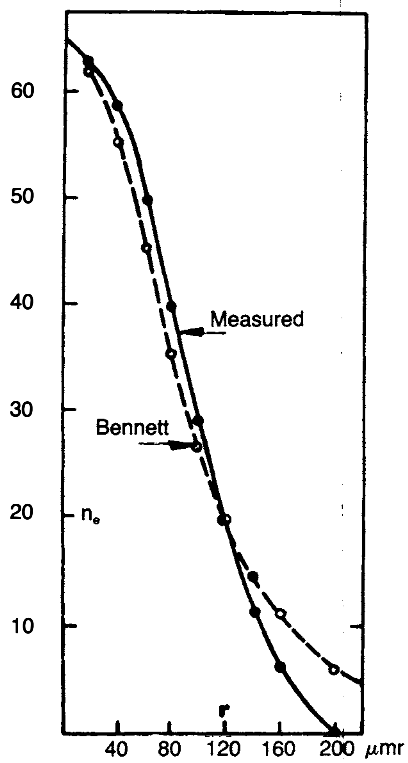
The author would reply that the key to studying properly the plasma focus is in space-time resolution of the instrumentation. The Stevens spatial resolution in X-ray pinhole photography has been a factor of 10 better than any of the spatial techniques employed elsewhere. The Stevens neutron collimation gives the best (as far as we know) neutron spatial 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. 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

FIGURE 17

Plot of electron density N_e versus distance r from the source axis

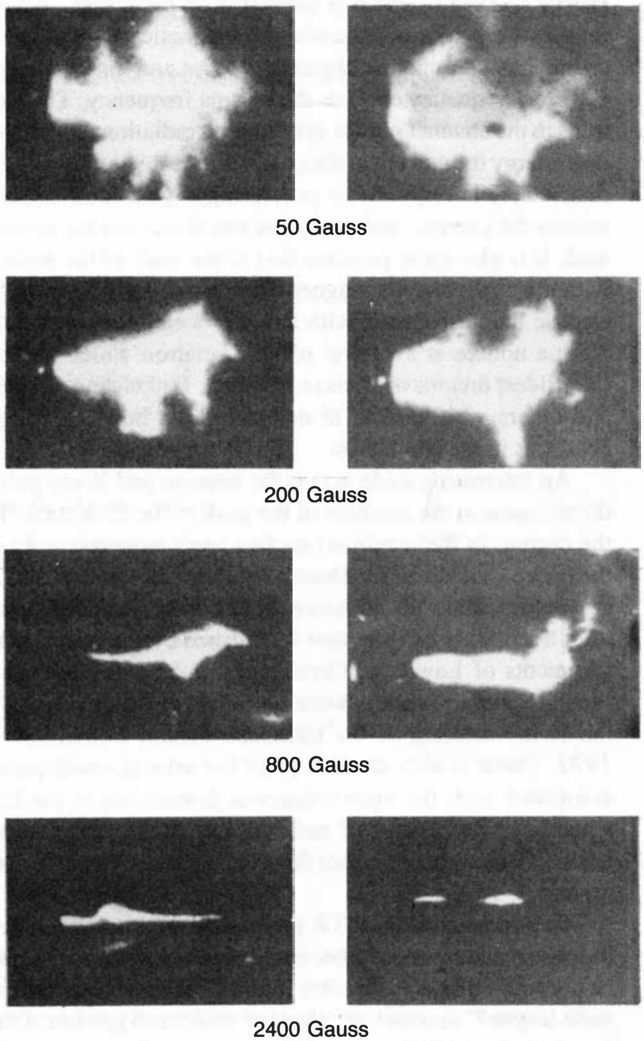
(which is taken to correspond to point of peak intensity)



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 $n_e = n_0(1 + bn_0r^2)^{-2}$; the constant b is obtained by a best-fit of emission coefficient within a distance $r \leq 0.2$mm from source axis. Vertical scale n_e is in arbitrary units.

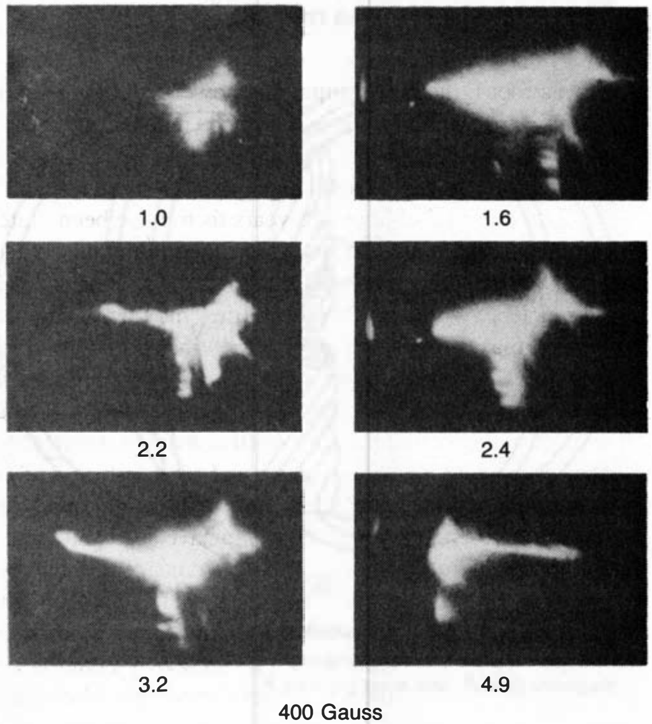
been experimentally staring us in the face, starting with the bouncing of plasmoids off each other (like billiard balls) in 1955, continuing with the fountain pinch, the filaments of Kvartskava, the plasmoids of Wells, the vortex filaments in the plasma focus current sheath. And now the sharpest of all 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 is shown in **Figure 17** along with a computed "Bennett" profile. It must be remembered that the plasma nodule channel contains, according to the best estimates, both B_z and a B_θ of magnitude up to ~600 MegaGauss, and vorticity and mass velocity and current vastly exceeding the Alfven limit, and that it lasts approximately ~1 nanosecond. 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, see *EIR*, Feb. 8) are also very sharp.

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_0h is constant.

FIGURE 19



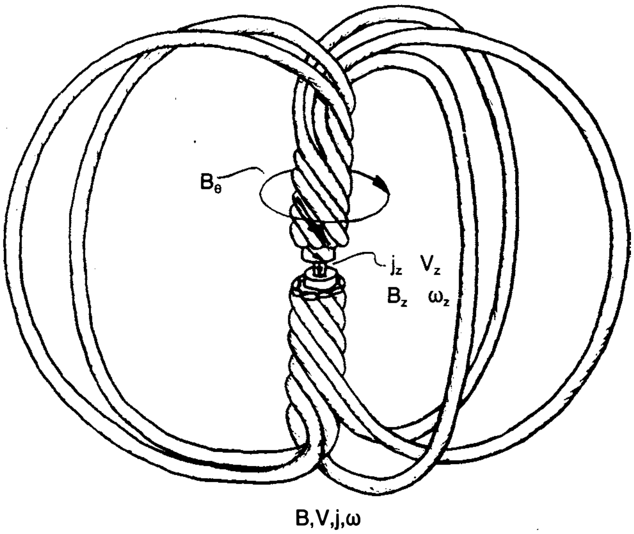
Plasma camera photographs at 0.1 microsecond exposure of the electron density distribution of a copper plasma taken at various times after the gun fires. Plasma, injected from the right, is seen at times of 1.0, 1.6, 2.2, 2.4, 3.2 and 4.9 microseconds as it moves across a 400 Gauss field. The protuberances extend in the velocity cross magnetic field (VXB) direction, downward here. The gun is in opposing polarity.

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. 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, 0.1 microsecond 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 experi-

FIGURE 20
Diagram of a plasma nodule



In this 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.

mental 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.

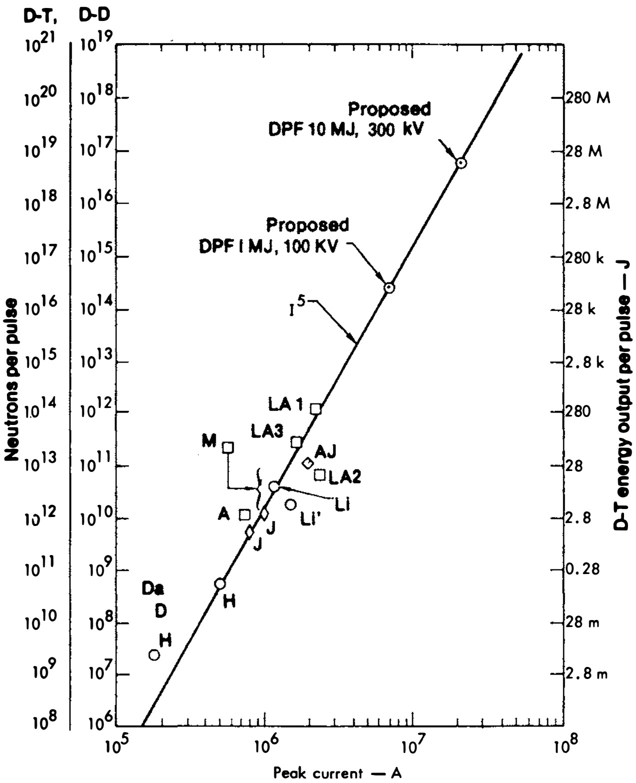
In the pinch phase of the plasma focus when the left-handed and right-handed vortex filament pairs in the current sheath are beginning to consume each other and destroy these ingeniously constructed current-conducting paths, it is quite conceivable that a few unpaired filaments survive, unscathed by 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**. 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 ~10 microns. During the formation of this nodule the electron temperature remains that of the current-sheath vortex filament (~20 electron volts, the ion energy ~50 electron volts). 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 ~5-30 nanoseconds, 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. 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 1950s.

An interesting aside is that the neutron and X-ray pulses do not come at the moment of the peak in the dI/dt 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 nanoseconds after the peak of the dI/dt 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 European Fusion Conference in 1970. There is also an dI/dt 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 nanoseconds 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 5 kilojoule 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 machine thus operated and reported. 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 Energy Research and Development Administration CTR magnetic confine-

FIGURE 21

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



ment program to pay for such a program. Figure 21, which is taken from a Lawrence Livermore Laboratory design study, indicates that a "breakeven" machine of the type designed will occur at about 4 megajoules and 16 megamperes.

The extrapolation in neutron production from Mather's last 400 kilojoule machine to the breakeven machine represents the same range (~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 $I_p=16$ megampere machine at considerably less than 4 megajoules. The cost would be about $5 million 1977 dollars and the time about three years.

Greatly anticipated by the profession are the neutron yields of the 1 megajoule plasma focus now just going into operation at Frascati. The Lawrence Livermore Laboratory new 1 megajoule plasma focus has been operating with one-quarter of its capacitor bank and at 25 kilovolts (instead of 40 kilovolts) at about 1.3 megamperes, 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. The author believes that the calculations are based on a model for the neutron producing 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. The deuteron beam at the nodule is of the order of 10^5 amperes and 10^9 amperes per sq. cm.

For at least two years J.S. Luce, R. Gullickson, B. Freeman, O. Zucker, and H. Sahlin at Lawrence Livermore Laboratory 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 Lawrence Livermore Laboratory 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 the Naval Research Laboratory and Sandia National Laboratory reported enthusiastically evidence of "filaments" in their relativistic pinches. At the 1971 American Physical Society 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 Lawrence Livermore 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 kilojoule), 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 megajoule, 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 Livermore 1 megajoule machine on only one-quarter of its cylinders is turning in some superlative laps where he extracts 75% 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. 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 the Energy Research and Development Administration (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 Fusion Power Coordinating Committee, 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, stellarator, 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 U.S.S.R. had provided for Lev Artsimovitch, the super-salesman of the Tokamak, the ultimate sanctification of laying him out alongside 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, Livermore, Los Alamos, 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!

*Because there are references to figures that appeared in the previous two installments, we are continuing to number figures consecutively.

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 of X-rays and radio-frequencies.

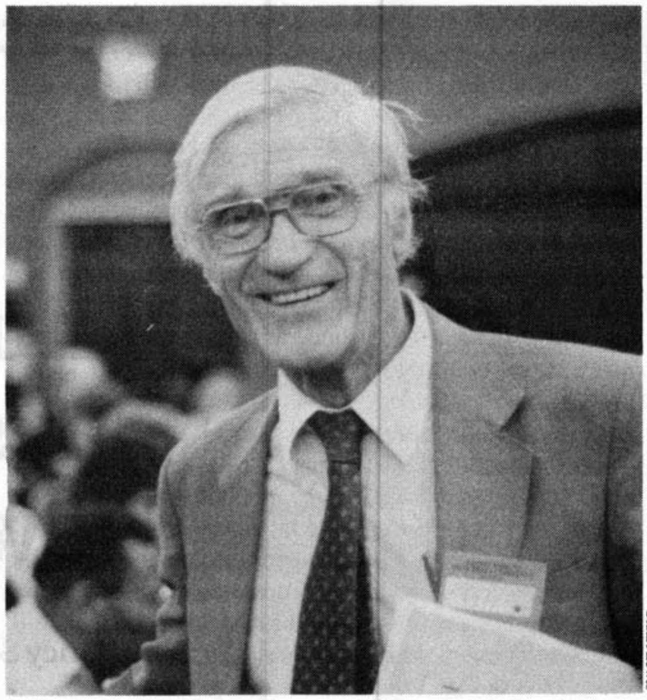
Boris Kadomtsev in his analysis likened the process to the solar flare phenomenon and posed again the perennial obstacle in the understanding of how two juxtaposed plasma filaments carrying current in the same direction, where there is a conducting plasma cushion between them, can come together so fast. 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 of 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 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 10 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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