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CURRENT PROBLEMS IN RESEARCH

Stabilized Pinch and Controlled Fusion Power

Study of the pinch effect has caused ups and downs in the hopes for building a thermonuclear reactor.

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Controlled fusion power (*1*) is an exciting possibility, because the proposed fuels, deuterium and tritium, are obtainable in almost unlimited supply from the ocean. Unfortunately, the operation of a fusion reactor is unlike that of a fission reactor in that the reaction cannot be initiated simply by assembling the fuel elements. Only by preheating the fuel to from 10^8 to 10^9 degrees Kelvin and maintaining such temperatures at least for an appreciable fraction of a second can fusion power be generated in a controllable manner. The stabilized pinch is one of the several "magnetic bottles" that have been proposed to solve the heating and containment problem. Large-scale pinch research is being conducted by the Atomic Energy Commission at the Berkeley, Livermore, and Los Alamos sites of the University of California.

When a strong current is passed through a tube filled with ionized gas, or plasma, a contraction of the plasma column results (Fig. 1). This so-called "pinch effect," first described by Willard Bennett (*2*) in 1934, has turned out to have many useful features. The large current in the pinch column serves to heat the plasma, as does the compression associated with the pinching. A toroidal stabilized pinch (Fig. 2) is an example of a perfectly closed magnetic bottle. The magnetic field and plasma distribution in this bottle is nearly optimal, from the point of view of reactor economics. Such considerations have kindled high hopes for the pinch as a successful fusion machine.

In what follows it will perhaps become clear that the achievement of a power-producing pinch device is not really very close at hand. This result is not disappointing, since present experiments are not meant to fall into the realm of reactor technology but into that of basic plasma research. The substantial scale on which pinch research is conducted the world over reflects not so much the imminence or inevitability of success as the high potential value of knowledge about thermonuclear plasmas. The same comment applies in the case of the various other magnetic bottles that are being studied intensively at present (*3*). In each instance a plausible design for an ultimate power-producer serves to orient research, but the immediate objective is to learn about some feature of plasma physics. What composite or entirely novel fusion machine will emerge from this basic research effort remains to be seen.

The Unstable Pinch

In the course of early experiments with the pinch effect (*4*) it was found that the simple pinch configuration (Fig. 1) is violently unstable. The plasma particles are indeed kept tightly in the magnetic bottle while it lasts, but the bottle itself soon falls apart. In the experiments, destruction occurred after a few microseconds—an interval far short of useful thermonuclear reaction times. The predominant instability was found to be the "sausage" mode predicted by the theory of Kruskal and Schwartzschild (*5*) (Fig. 3*a*). The transient plasma temperatures which the pinching process would create before breakup of the configuration were also estimated on a theoretical basis (*6*). High-powered experiments to investigate the predicted plasma heating effect were soon under way.

During 1955, pinches at Berkeley and later at Los Alamos were found to emit large quantities of neutrons. It was thought reasonable to conclude that a thermonuclear plasma of some millions of degrees had been achieved. Experiments on the timing, symmetry, and localization of the neutrons (*7*) seemed to confirm the thermonuclear hypothesis. We noted, however, that neutrons could be produced under conditions where the theory clearly predicted nonthermonuclear plasma temperatures. Thanks to some lingering doubts on this point, a nuclear track plate experiment was done in Berkeley in late 1955, which showed that the neutrons were indeed produced by a "spurious" effect (*8*).

It may be helpful here to explain just why the distinction between thermonuclear and nonthermonuclear neutrons is of consequence in fusion research. The production of fusion reactions as such is not very difficult and can be accomplished by any number of particle accelerators the world over. A beam of deuterons is accelerated, say to 100 kev energy, and allowed to impinge on a cold deuterium target. Some of the incident deuterons will fuse with target deuterons, releasing energetic neutrons. The difficulty with this approach is that more energy is always degraded into heat than is regenerated by the fusion reactions. On such a basis it is impossible to produce power. In a power-producing reactor the deuterons must be able to collide with each other many times without degradation of energy (*1*). This requirement defines a *thermalized* assembly of reacting particles—a so-called thermonuclear plasma.

A thermal deuterium plasma does not

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produce measurable neutron yields below a few million degrees temperature. Just above this threshold the increase of the yield with increasing temperature is extremely steep. If a given neutron-emitting plasma is also a thermal plasma, the plasma temperature can be calculated with high precision from the neutron yield. Such a "neutron thermometer" gives some measure of the degree of progress toward practical thermonuclear conditions. If a neutron-emitting plasma is *not* thermalized—that is (if the neutrons are caused by a small population of energetic deuterons reacting with an otherwise cold plasma—then the yield is obviously not indicative of high plasma temperature or of progress toward the conditions of a fusion reactor. In that case one speaks of spurious or nonthermonuclear neutron yields.

The nuclear track plate experiments which were done in 1955 on the unstable pinch showed that the neutrons were generated by a 10^{-3}-percent population of deuterons moving with 40 kev mean energy in the direction of the pinch current, rather than by a uniformly hot plasma of 10 million degrees (or 1 kev) temperature. The most plausible explanation (*8*) seemed to be that the energetic deuterons were accelerated by intense local electric fields set up at the unstable constrictions of the pinch column (Fig. 3*a*). How high a plasma temperature has actually been reached in unstable pinch experiments is not known. Part of the difficulty is that the spurious neutron yield masks any true yield that may be coming from the thermalized part of the plasma. In this way the large neutron emissions, which were welcomed with enthusiasm at first, have become a nuisance to the experimenter.

Soon after the Berkeley experiment,

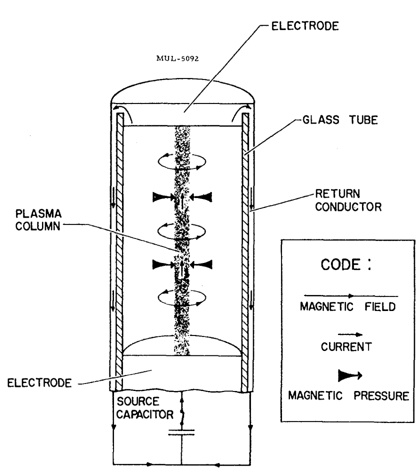


Fig. 1. The simple, unstable pinch.

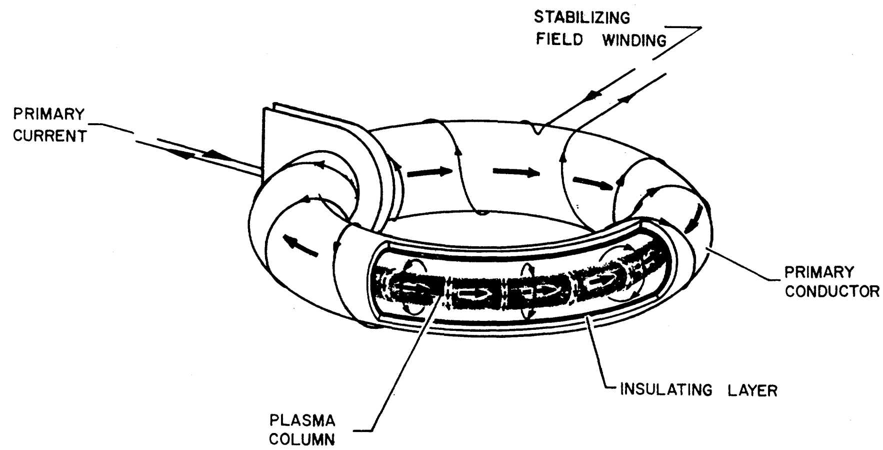


Fig. 2. A toroidal stabilized pinch. The primary current on the shell induces a longitudinal opposing current in the plasma, which pinches the discharge. During pinch formation, the longitudinal stabilizing field is trapped in the plasma, and the current in the stabilizing winding comes to a stop. At the same time, an azimuthal surface current appears on the plasma.

I. V. Kurchatov created a sensation at Harwell (*9*) by reporting on neutron emission from unstable pinch devices in the U.S.S.R. It turned out that the Russian pinch program had also undergone a cycle of high expectations and sobering afterthoughts some years before. We were particularly impressed by the good judgment of the Russian scientists in doubting that a thermonuclear plasma had been achieved even though they did not have available the definitively nonthermonuclear evidence of the nuclear track plate experiment.

Stabilization of the Pinch

Early in 1956 the philosophy of the United States pinch program underwent an important development. Heretofore the instability of the pinch effect had been regarded as a necessary evil. The principal aim had been to achieve and study thermonuclear plasma conditions during the very short time interval between pinch formation and breakup. It was now recognized that the pinch could be made stable.

The retarding influence of a longitudinal magnetic field on pinch instabilities had been calculated in 1953 by Kruskal and Tuck (*10*). During 1954, the importance of trapping a longitudinal magnetic field *inside* the pinch column was emphasized by Morton Levine, in an unclassified Tufts College report (*11*). It was also shown by Levine (*12*) and others that a close-fitting cylindrical return-conductor on the pinch tube would create a stabilizing effect. A rigorous mathematical theory of pinch stability was produced by Marshall Rosenbluth (*13*) in the spring of 1956. When a longitudinal magnetic field is trapped inside the pinch column, it is fairly obvious that the sausage instability mode is inhibited (Fig. 3*b*). In this case the most violent remaining instability is the "kink" mode of Fig. 3*c*. Rosenbluth proved that by the joint influence of the trapped longitudinal magnetic field and a close-fitting return conductor, the kink instability could be suppressed (Fig. 3*d*), as could all the other less violent modes. The detailed conditions under which this stable regime is achieved are quite restrictive. No pinch is stable if the radial compression is greater than 5:1 or if the plasma pressure exceeds the longitudinal magnetic field pressure. In addition, it is essential that there be little or no longitudinal magnetic field in the region outside the pinch column.

The predictions of the Rosenbluth stability theory have been investigated experimentally at some length (*14*). The procedure was to wrap a solenoid around a linear pinch tube containing neutral gas and to pass a slow-rising current through this winding. A longitudinal magnetic field then appeared in the tube. At this point we would ionize the gas and pass a fast-rising pinch current through it. A plasma column was then formed as usual, with the longitudinal magnetic field trapped inside. Trapping of magnetic field in plasma occurs, of course, by virtue of the electrical conductivity of the plasma. A more familiar form of the same phenomenon is the so-called "skin effect." A high-frequency current can flow along a conductor only in a shallow surface layer, because the magnetic field of the current cannot pass readily into the interior. In the case of stabilized pinch the situation is reversed: the magnetic field is prevented from passing rapidly *out of* a conductor—namely, the pinch. As the pinch is formed, a layer of azimuthal skin current begins to flow around the plasma column. One can think of the azimuthal current layer as the field-generating solenoid that accompanies the entrapped longitudinal magnetic field.

As the pinch column contracts, the longitudinal magnetic field grows in intensity, so that a magnetic back-pressure develops. The pinch compression proceeds to a point where the pressure of the trapped longitudinal field and plasma precisely equals the pressure of the azimuthal field outside the pinch column. In the experiments, the degree of compression was controlled by altering the magnitude of the initial longitudinal field. When the longitudinal field was made small or null, the resultant pinch proceeded to a high compression and was almost immediately unstable. When the conditions of the Rosenbluth theory were met, we observed a transient interval of stability, lasting some ten times longer than the life-time of the discharge when unstabilized.

The importance of avoiding longitudinal magnetic field outside the pinch column was also demonstrated unequivocally by the experiments. When a pinch was formed, all the longitudinal field passing through the gas would be trapped inside. Additional magnetic field was prevented from entering the discharge tube during the pinch time because of the solid conductor shell surrounding the tube. However, there remained a small amount of longitudinal magnetic flux in the cross section of the glass itself. The passage of this flux into the region between the pinch column and the tube wall had a critical influence on the stability of the discharge. We were able to show that under otherwise identical conditions the pinch would be stable or unstable depending on whether the glass wall of the discharge tube was thin or thick.

This disruptive influence of magnetic field outside the pinch column manifested itself in still another interesting way. By means of a small search-coil, we observed that in a thin-walled discharge tube the magnetic field near the tube wall would drop to very low values during pinch compression. This was exactly as desired. For stable compressions, the signal remained near zero for a while and, if the pinch current was maintained sufficiently long, would then actually swing negative (Fig. 4*a*). Kerr cell pictures taken at the time of the anomalous negative signal showed that the pinch had wrapped itself into a helix (Fig. 4*b*). The explanation was not difficult to find. Because of the poor electrical conductivity of the plasma, neither the longitudinal magnetic field nor the plasma itself could be expected to remain perfectly trapped in the space of the original pinch column. A diffuse layer of mixed longitudinal and azimuthal magnetic field was soon formed at the surface of the discharge. As the layer broadened, the configuration acquired unstable tendencies, precisely like those of an undiffused pinch with some longitudinal field outside it. Eventually the kink instability developed. As predicted by Rosenbluth's theory, the kinks aligned themselves in such a way as to form a helix. This helix, acting as

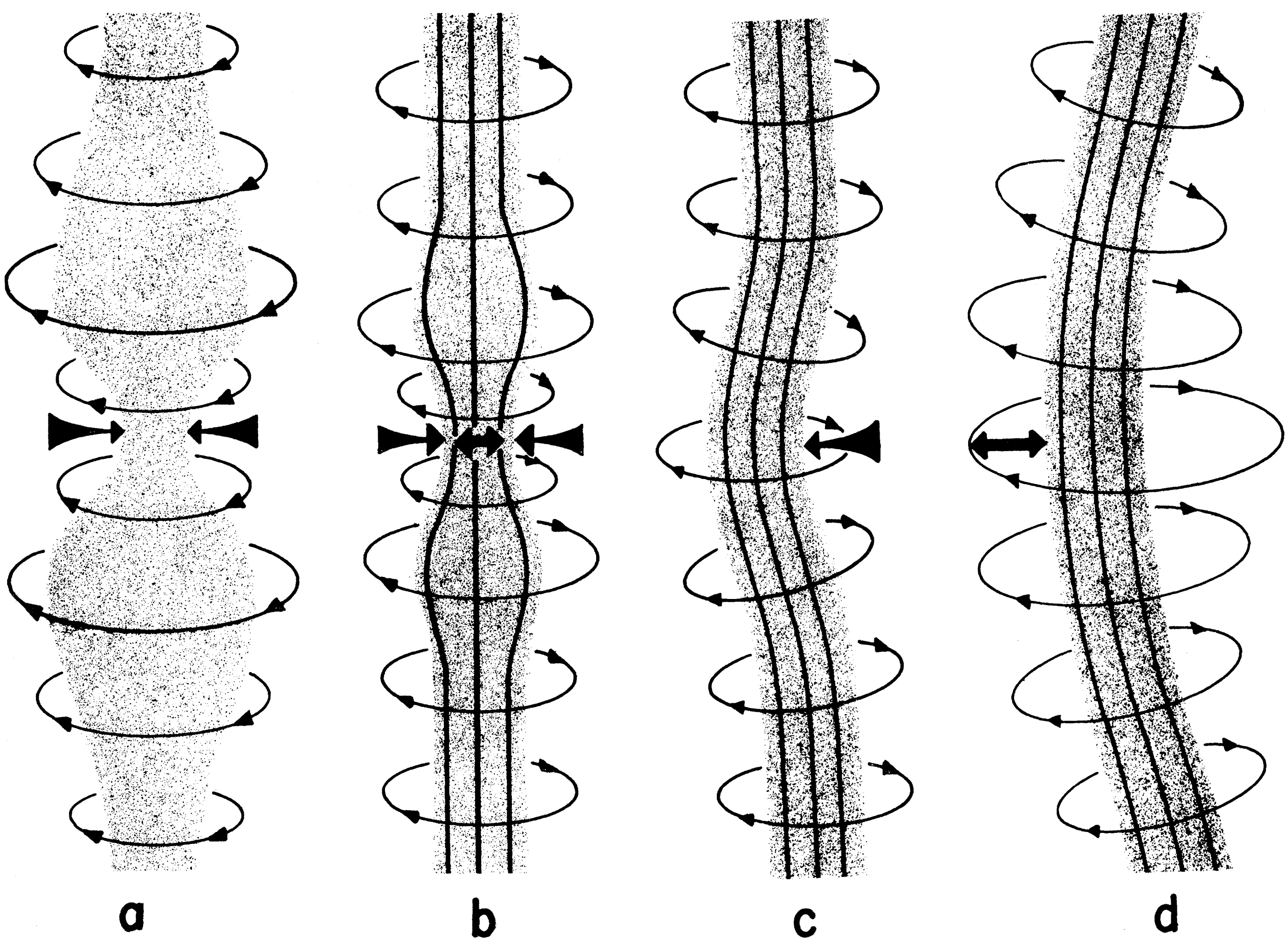
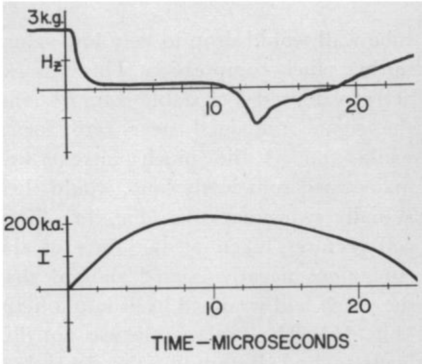


Fig. 3. (a) The sausage mode of the simple pinch; (b) the stabilization of the sausage mode by an included longitudinal field; (c) the kink mode; (d) the stabilization of the kink mode by a conducting shell. The heavy arrows indicate magnetic pressures.



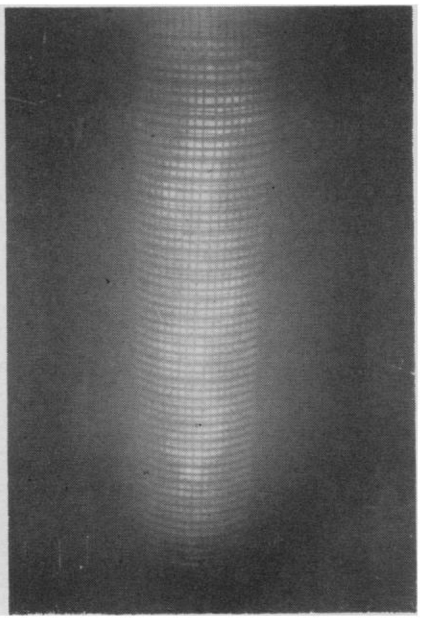


Fig. 4. (a) (Above) Variation of the longitudinal magnetic field at the tube wall of a stabilized pinch. The sudden negative swing of the signal indicates the onset of a helical instability mode. (b) (Right) A Kerr cell picture of the helical instability.

a kind of solenoid, produced a negative longitudinal magnetic field at the tube wall.

The maximum stable time of the pinch was now seen to depend on the rapidity with which the original pinch configuration became diffuse (Fig. 5). As is well known, the duration of diffusion phenomena in a system increases with the square of the linear dimension. For instance, the head of a pin will cool in a millisecond when immersed in water, while heat diffusion out of a large cannon ball may require a minute or more. In the same way, a sufficiently large pinch device can obviously be kept stable long enough to produce power.

At the outset of the pinch program it was recognized that the life-time of an *unstable* pinch could be made appreciable simply by building a large device. In this case the instability growth time depends essentially on the transit time of hydromagnetic waves across the pinch column. Consequently the period of useful plasma containment increases directly as the linear dimension of the system. Early calculations demonstrated that a reactor of the unstable pinch type would have to be of enormous size. Each cycle of operation would liberate an amount of energy comparable to the yield of a hydrogen bomb. When contrasted with such an infernal machine, a moderately large-scale version of the stabilized pinch experiment seemed almost reasonable, though economically still unattractive. From the economic point of view, the really hopeful approach was to try to prolong the stable time of the pinch, not by increasing its size very much but, rather, by reducing the diffusion constant of the plasma. The logic of this procedure can be made appealing by recourse to the heat diffusion analogy: If one wishes to keep cold ice cream available for a certain length of time, it is clearly more practical to find a thermos bottle than to fill up the bathtub.

The diffusion constant that governs the deterioration of the stabilized pinch is the electrical resistivity of the plasma. If the plasma resistivity is large, the stabilizing field diffuses rapidly out of its confinement, just as the magnetic field of a pulsed solenoid decays rapidly if the circuit resistance is large. The resistivity of a plasma can be calculated from the number-density and the mean free path of the electrons that carry the current. On the basis of electron-ion scattering cross sections it is easy to show (*15*) that plasma conductivity improves with the 3/2 power of the temperature and does not depend very much on density. A deuterium plasma of 10 million degrees has the conductivity of standard copper. Since the conductivities observed in the stabilized pinch experiments were more than a hundred times lower, corresponding to about 300,000°C, it was reasonable to anticipate a great improvement in pinch diffusion times as soon as 10- to 100-million-degree temperatures could be reached.

In diffusing from a stable to an unstable configuration, the magnetic fields of the pinch lose a certain fraction of their energy content. We showed that the missing energy, delivered to the plasma in the form of ohmic heating, is always of just the right magnitude to raise the plasma to a useful temperature. Here it is assumed that the heating rate is sufficiently high to overcome loss mechanisms such as bremsstrahlung. A detailed calculation of a pinch heating and reaction cycle based on the diffusion principle has been made by Rosenbluth (*16*).

If high plasma temperatures are to be maintained in the pinch during long reaction times, it is of course essential to eliminate heat conduction along the longitudinal field lines, into the electrodes. For this purpose one passes from linear to toroidal geometry (Fig. 2). The toroidal pinch tube is a kind of pulse transformer in which the conductor shell is the primary and a pinched ring of plasma constitutes the secondary. Separation of the primary and secondary is achieved by means of a toroidal insulator tube or lining. An iron core is often used to improve the coupling between the primary current and the pinch current. The physics of the toroidal pinch is essentially that of a linear pinch having infinite length.

The development of the stabilized pinch reactor scheme has been the major original contribution of United States pinch research to fusion reactor technology. The publications of the U.S.S.R. have dealt mostly with powerful unstable discharges (*17*). Several papers (*18*) have appeared describing pinches partly stabilized by longitudinal magnetic fields, but the possibility of achieving complete stabilization by avoiding longitudinal magnetic field outside the pinch appears to have been overlooked (*19*). The pinch research program of the United Kingdom prior to 1957 was oriented toward taking advantage of partly unstable discharges. The plan of attack was to build large toroidal discharge tubes and to allow the unstable pinch to "wriggle" within these confines. In this way, powerful shock heating as well as a limited form of plasma containment could be anticipated.

High-Powered Stabilized Pinches

Since the fall of 1956, the controlled fusion research efforts of the United States and the United Kingdom have been brought into close collaboration. This joining of forces has proved especially valuable in the field of pinch reach, which is the British specialty. By the end of 1956, the size of American pinch installations was still extremely modest. Almost all the experiments had been done with tubes of from 2 to 4 inches in diameter, powered by capacitor banks in the 10^4-joule range. The British were already using tubes a foot in diameter and were planning Zeta, a toroidal pinch device with a 3-foot bore, powered by a 1-million-joule capacitor bank. Among the fruitful techniques developed at Harwell were the use of all-metal pinch tubes and the operation of pinch discharges in very low densities of deuterium.

The American contribution to the joint research effort was a dogmatic insistence on complete pinch stabilization. The British scientists had already done some thinking along this line (*20*) and were readily converted. Zeta, which originally had been planned as the most advanced of the "wriggling" pinches, underwent some rewiring and turned out to be the most advanced of the stabilized pinches. Experimentation with Zeta began in the late summer of 1957 and immediately yielded important results. In the small pinch devices, the time of stable operation had been only about 10 microseconds, or about ten times longer than a typical instability growth time. Zeta, being ten times larger in diameter, remained stable for a millisecond, or a hundred times longer than a typical instability growth time. In this way, the gross stability of the configuration was far more clearly demonstrated than in the smaller experiments. Much to our disappointment, the electrical conductivity in Zeta turned out to be rather worse than it had been in the little pinch devices. A temporary distraction from this result was afforded by the observation of neutrons coming from the discharge (*21*).

The theoretical maximum plasma temperature in Zeta was about 20 million degrees. It was therefore conceivable that the observed neutrons might be coming from a 5-million-degree thermonuclear plasma. Measurements on the Doppler broadening of impurity spectra supported this possibility. Certain particulars in the timing and magnitude of the neutron signal seemed odd, but we were all sufficiently impressed by the performance of Zeta to entertain the thermonuclear hypothesis.

Around the Christmas season of 1957, Sceptre, a toroidal stabilized pinch of 12-inch bore, began to yield neutrons (*22*), as did Perhapsatron S-3 in the 2-inch size (*23*) and Gamma Pinch (*24*) at 4 inches. Even more surprising, Columbus S-2, a *linear* stabilized pinch (*25*) was emitting neutrons, though such devices had not been expected to reach thermonuclear temperature, because of heat losses to the electrodes. In the Los Alamos experiments (*23, 25*), the magnetic field distributions of the pinches were studied and were shown to imply plasma pressures indicative of thermonuclear temperature. In all the experiments the electrical conductivity proved to be about the same—namely, far below what the classical theory would predict at the 3- to 6-million-degree temperatures required by a thermonuclear explanation of the neutrons.

The conductivity results were taken by us as indicative of rather poor plasma conditions, or at least of poorly understood conditions, and as a result a spirit of cautious skepticism developed at Livermore (*26*). The early observations made on Zeta had been somewhat confidence-inspiring, but the wealth of neutronics data which was now becoming available from the smaller machines showed that neutrons were often produced under extremely unsanitary conditions. We were soon led to conclude

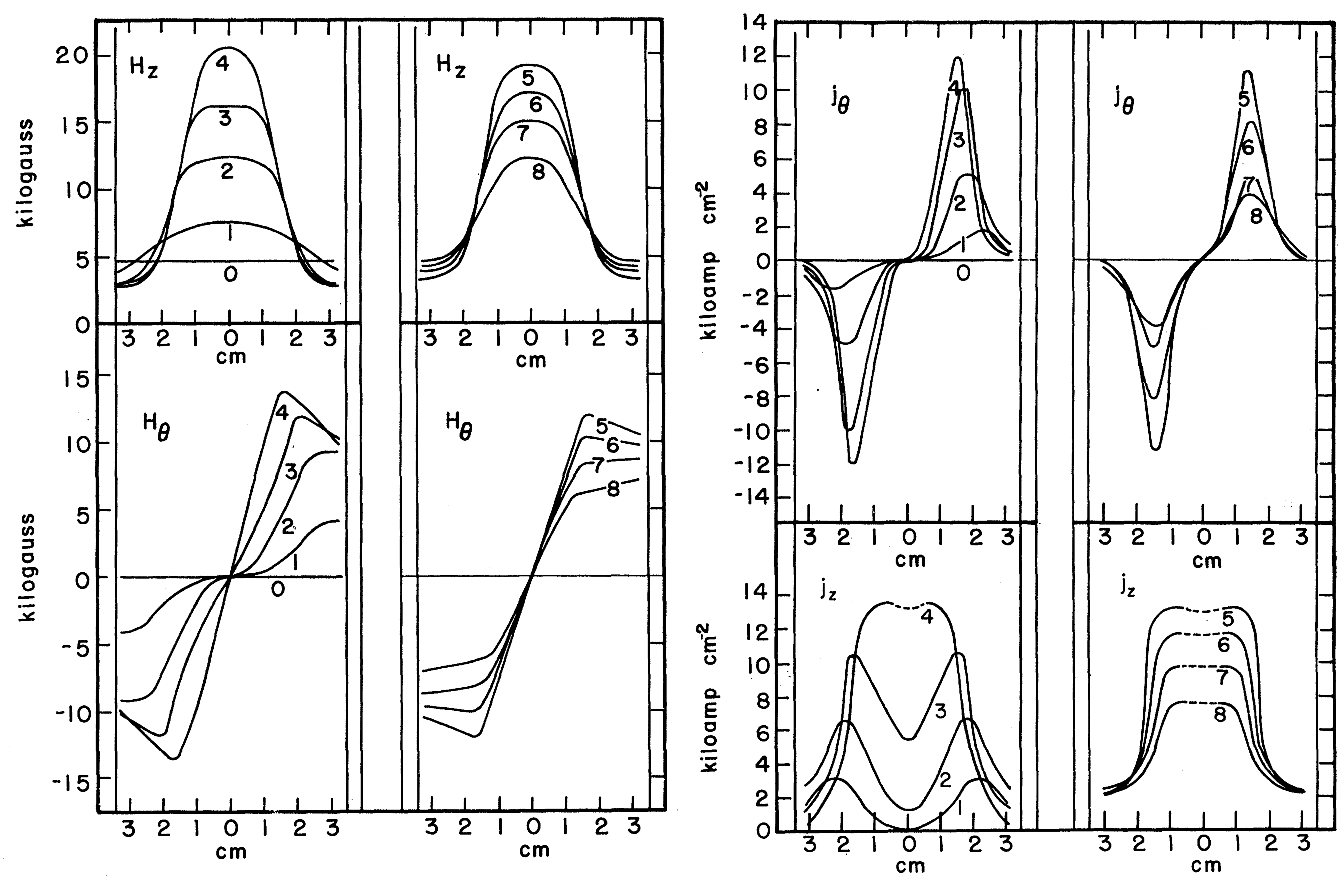


Fig. 5. Magnetic field and current distributions in a linear stabilized pinch, as measured with search-coils. The curve labels refer to microseconds after pinch initiation. The longitudinal and azimuthal magnetic fields are shown interdiffusing, but the current cycle is kept short enough to avoid instability.

that the stabilized pinch was subject to a spurious neutron production mechanism, just as the unstable pinch had been. All the neutron-emitting machines had certain important parameters in common, such as the magnitude of the pinch current, the number of plasma particles per unit length of the discharge, and the proportion of the pinch cycle time to the square of the tube radius. The neutronics data from all the machines showed a remarkable consistency in their dependence on voltage, pinch compression ratio, plasma density, and impurity admixture. Accordingly, if the thermonuclear claim could be made for any of the machines, it had to be made for all of them. In view of the accumulating discrepancies, we thought it more likely that all the machines were equally subject to some nonthermonuclear mechanism of neutron production.

The Doppler-broadened spectra obtained with Zeta could be explained in terms of local plasma turbulence just as readily as in terms of high temperature. The large apparent plasma pressures found at Los Alamos by means of magnetic probe analyses were interpretable as pressures of turbulent motion. Conversely, it was argued that the low temperatures estimated on the basis of the electrical conductivity were unrealistic, because resistivity might be enhanced by various plasma oscillations. Arguments based on conservation of energy seemed to indicate very high temperatures, but it was shown on Gamma Pinch that a large anomalous heat-transfer effect was taking place between the discharge and the tube walls. Still another debatable estimate of temperature was afforded by the degree of stripping of impurity ions, such as oxygen. The presence of three-, four-, and five-times-stripped oxygen and the absence of the six-times-stripped ion in Zeta were interpreted by various methods as implying temperatures of anywhere from 200,000 to 5 million degrees.

Recently the edge of the controversy has been dulled somewhat by the discovery on Zeta that the observed neutrons are caused by a small population of high-energy deuterons accelerated in the direction of the current (*27*). The experiment, done with a cloud chamber, was very similar to the nuclear track plate experiment, which had earlier diagnosed the neutrons from the unstable pinch as nonthermonuclear. Shortly after the Zeta results were known, the same experiment was done at Los Alamos on Perhapsatron S-4, a 4-inch toroidal pinch (*28*). The Los Alamos findings have proved identical with those obtained on Zeta. The mechanism of deuteron acceleration is still undetermined. There is some evidence both for and against a simple "running away" of deuterons in the applied electric field of the discharge.

The dillusioning experience with neutrons from the stabilized pinch, coming on top of the similar experience with neutrons from the unstable pinch, seems to convey a lesson. Heretofore the interpretation of neutronics results has been approached on the basis of a preconceived model, the thermonuclear plasma. On measuring a given neutron yield, experimenters have quoted a corresponding temperature. The logic of this procedure is extremely precarious, especially in the case of small neutron yields. Most of the fusion reactions of a low-temperature thermonuclear plasma are produced by particles far out in the high-energy tail of the Maxwellian distribution. Even on observing a neutron yield produced by an isotropic deuteron population that might perhaps constitute the high-energy component of a thermonuclear plasma, one cannot logically demonstrate the presence of the Maxwellian distribution from the presence of its tail. Judging from present indications, the pure Maxwellian energy distribution may turn out to be an experimental rarity, rather than the most likely possibility. One is forced to conclude that temperature estimates should be based, not on neutronics, but on a thorough study of bulk plasma properties, coupled with a theoretical understanding of the observed phenomena. Unfortunately, scientific knowledge of this kind is only slowly becoming available in the case of the stabilized pinch.

Electrical conductivity measurements on Zeta and the other recent devices all point to temperatures of about 100,000 degrees, an even lower figure than characterized the old linear stabilized pinch experiments. This result carries with it a suggestion that conditions are worse, at least in some respects, in the high-powered pinch experiments of 1958 than in the low-powered experiments of 1956. One possibility is that plasma temperatures are actually lower in the high-powered machines. A second and perhaps more likely possibility is that actual plasma temperatures differ from those computed on the basis of the classical theory of conductivity. This alternative is supported by recent analyses of impurity stripping in Zeta, which indicate temperatures between 300,000 and 500,000 degrees.

While the so-called "stabilized" pinch has been shown to be highly stable in a gross sort of way, evidence is now accumulating that small-scale turbulence exists within the gross configuration. Under these circumstances, it is not surprising that the electrical conductivity of the discharge is low and becomes lower at higher power levels. If the mean free path of the current-carrying electrons is being kept short not by electron-ion collisions but by electron interactions with hydromagnetic and electrostatic plasma waves, then one may anticipate a consistent shortening of the mean free path as more energy is made available for the excitation of the waves. If this theory proves correct, then pinch research is on the threshold of an important plasma-physical discovery. At the same time, the existence of an enhanced resistivity effect at high power levels would raise doubts about the stabilized pinch as a long-time, high-temperature plasma container. In this context it should be recalled that the function of a magnetic bottle is just precisely the long-time containment of hot plasma, not the achievement of fusion reactions, which can be duplicated by a simple accelerator. Even if 100-million-degree plasmas were eventually produced by means of pinch experiments, the failure to achieve long-time stable containment in a device of reasonable size would eliminate the pinch as a fusion reactor scheme.

Current research on Gamma Pinch is yielding some suggestive results on the role of runaway electrons in the excitation of plasma waves (*14*), and we are looking forward with interest to experiments on a more powerful version of Zeta that will soon go into operation at Harwell. The opportunity for a broad review of world-wide pinch research will be afforded by the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, to be held in Geneva in September (*29*).

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Radiation and the Sex Ratio in Man

Sex ratio among children of survivors of atomic bombings suggests induced sex-linked lethal mutations.

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In species with an XX-XY type of chromosomal sex determination, such as man, the distribution to the offspring of radiation-induced, sex-linked mutations will differ according to the sex of the radiated parent. Furthermore, in the human species the nonhomologous nature of the X- and Y-chromosomes, coupled with the genetic inertness of the Y, permits the more frequent manifestation of sex-linked recessive genes in the heterogametic sex—namely, the male. This difference in manifestation and distribution of sex-linked genes would lead us to expect a significant change in the sex ratio if human populations were sufficiently exposed to mutagenic factors such as x-rays, or the fallout from weapon testing. Specifically, if fathers alone were exposed, an increase in the frequency of male births would be expected because sex-linked lethal mutants induced by the exposure would be transmitted only to the exposed fathers' daughters. If mothers alone were exposed, a decrease in the frequency of male births would be expected because sex-linked recessive mutants would more frequently find expression in the sons rather than in the daughters of the exposed females. If both parents were exposed, and if the effects of parental exposure were additive although not necessarily equal, we would expect a decrease in the frequency of male births; the change, however, would not be expected to be as pronounced as when mothers alone were exposed.

Assumptions

Several assumptions are implicit in postulating the changes just mentioned, and it seems important to state explicitly, at the outset, these assumptions, with a brief justification for each. Firstly, it is assumed that although autosomal lethal or semilethal mutations which are sex-limited may occur, their net effect is not such as to obscure the different effects on the sex ratio of paternal versus maternal radiation. Clearly, were this not so, the deviations postulated could be altered in degree or direction depending upon the relative frequencies of male-limited or female-limited mutants, or both. In view of the current state of knowledge of radiation genetics, it seems appropriate to assume that the predominant change in the sex ratio will stem from sex-linked rather than sex-limited effects.

Secondly, it has been assumed that the effect on the sex ratio of genes in the Y-chromosome is negligible, and that there exist no homologous portions of the X- and Y-chromosomes. The reasonableness of the former is supported by the knowledge that there is known, at present, no single, well-documented case of holandric inheritance, although this form of genetic transmission should be easy to recognize [for a discussion of Y-borne inheritance, see Stern (*1*)]. The legitimacy of the assumption that there is no homology between the X- and Y-chromosomes rests on the cytological work of Mathey (*2*) and Sachs (*3*).

Thirdly, and with reference to the exposure of both parents, it is assumed that sex-linked recessive mutants would outnumber sex-linked dominant mutations. The only animal for which data exist relevant to this assumption is *Drosophila melanogaster,* and here sex-linked recessives are estimated to be several times more common than sex-linked dominant mutants. In this connection, however, attention must be called to the

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