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The Leakage Problem in Fusion Reactors

To obtain useful power from thermonuclear reactions it is necessary to contain a plasma of ions and electrons in a magnetic bottle. The bottles leak, which presents the theoretician with a difficult task

by Francis F. Chen

For the past decade or so the competition between the U.S.S.R. and the U.S. in the exploration of space has attracted a great deal of public interest. The public is much less aware of another competitive international effort—which has also been in progress for about a decade—that may have greater ultimate significance. This is the effort to build a thermonuclear reactor, in which the reactions of nuclear fusion would be controlled to tap a practically unlimited supply of energy [see "Progress toward Fusion Power," by T. K. Fowler and Richard F. Post; SCIENTIFIC AMERICAN, December, 1966]. The general idea is to heat a plasma, or ionized gas, of deuterium or tritium to more than 100 million degrees centigrade and hold the plasma together by means of a magnetic field long enough for some of the ions to fuse, releasing energy in the form of radiation.

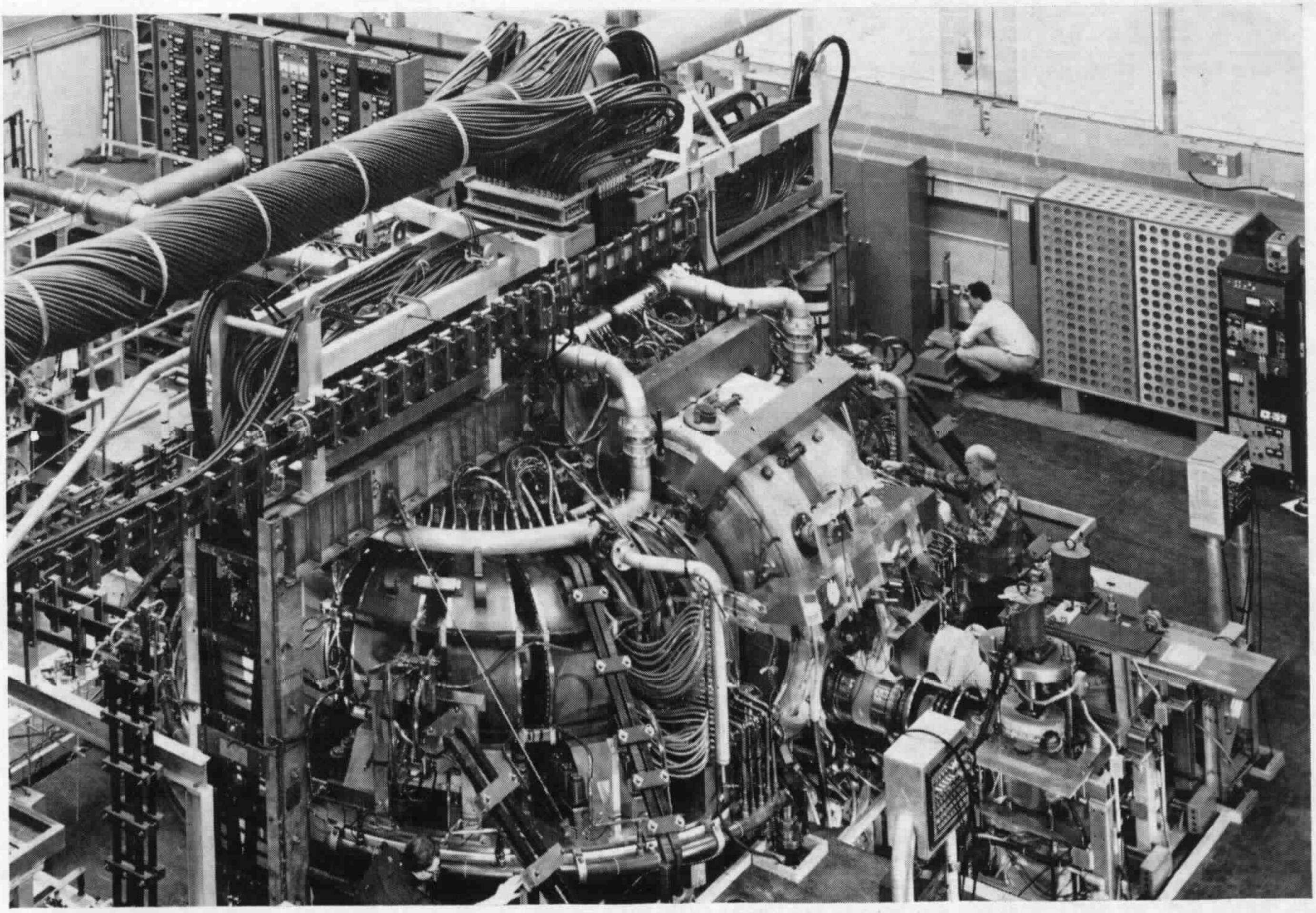
Almost from the outset the main obstacle has been the problem of confining the plasma. All kinds of "magnetic bottles" have been devised, and many have actually been built and tested, but so far all of them leak. The cause or causes of this mysterious leakage (called "anomalous diffusion" by workers in the field) have been sought for many years both in the large machines specifically built to produce fusion reactions and in smaller experimental devices. The recent theoretical discovery of "drift waves" in plasmas has thrown new light on the problem. This significant advance in understanding is the result of a truly cooperative international effort, in which the free exchange of ideas among physicists in various countries has played an essential role. Curiously, most of the research leading up to this insight was carried out in comparatively small-scale experiments.

The reason for the failure of early efforts to confine a hot plasma may lie in the way the discipline of plasma physics first developed. Because a plasma is dissociated into positively charged ions and negatively charged electrons, its behavior is much more complicated than that of an ordinary gas. To make the description of a plasma simple enough to handle, theorists began by regarding the plasma as a composite of two idealized interpenetrating fluids: a positively charged one representing the ions and a negatively charged one representing the electrons. This description is called magnetohydrodynamics, or simply hydromagnetics, and for a time all magnetic bottles were designed according to hydromagnetic theory. In the past few years, however, plasma physicists have discovered a new set of phenomena, called microinstabilities, that enter the picture only when the structure of a plasma is taken into account in considerably more detail than it is in hydromagnetic theory. Since magnetic bottles have been designed without a knowledge of these subtle microscopic effects, it is small wonder they leak. The purpose of this article is to describe how the new theory of microinstabilities differs from hydromagnetics, and to show how such a theory can be used to explain the persistent leakage of magnetic bottles.

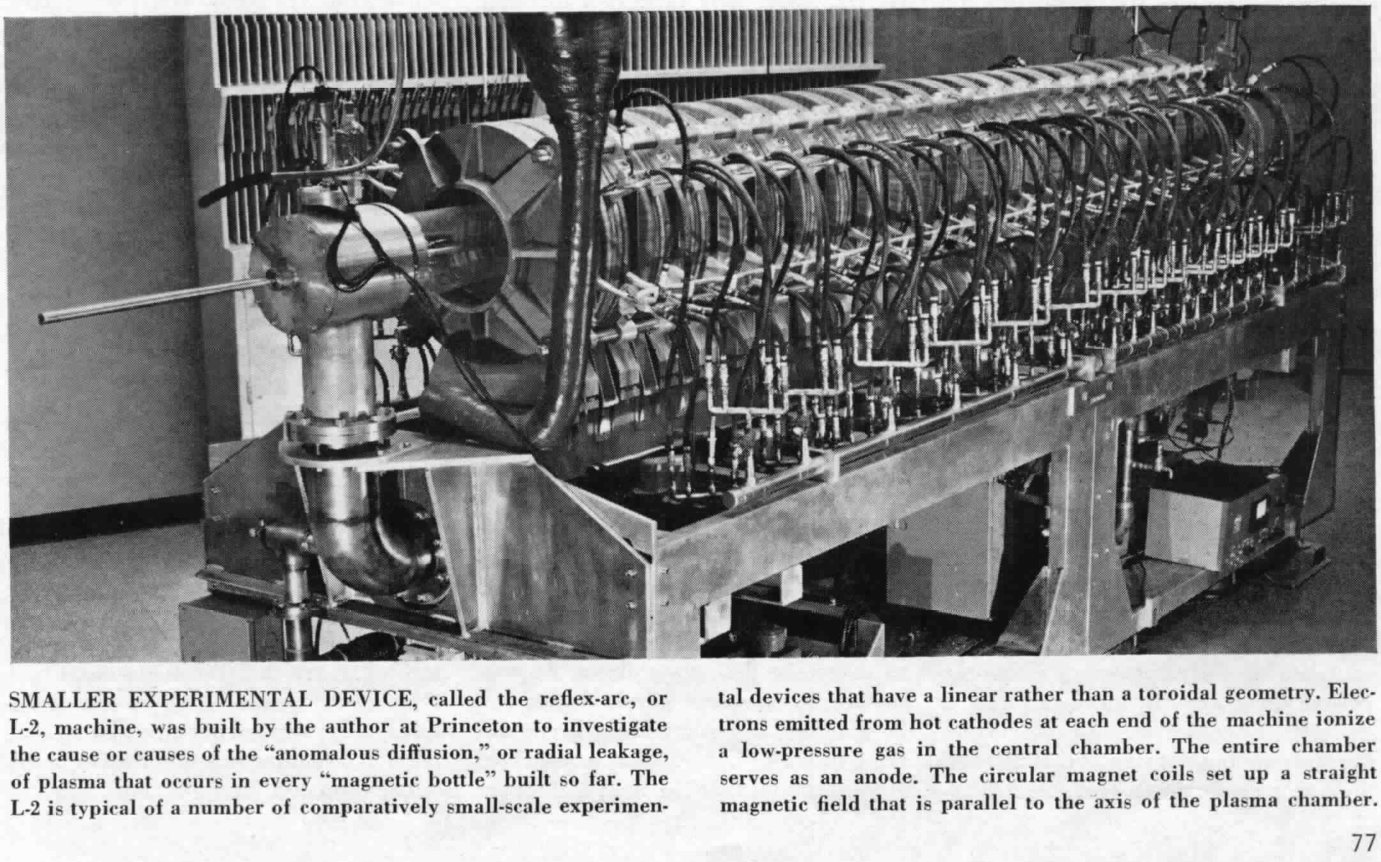
Let us begin by considering how a magnetic bottle is supposed to work. In a uniform magnetic field the ions and the electrons gyrate in opposite directions around the magnetic lines of force [*see upper illustration on page 79*]. Provided that the field is strong enough, the radius of gyration (called the Larmor radius after the British physicist Joseph Larmor) is quite small for the ions and much smaller for the electrons. Each particle can then be considered as being "stuck" to a line of force; if the lines were infinitely long, an isolated particle would not be able to move laterally across the field. The ions can collide with the electrons, however, and after each collision the center of gyration, or "guiding center," can shift to a neighboring line of force. By participating in a large number of collisions any given particle can slowly migrate to the wall of the container, where it will give up its energy before attaining the fusion temperature. This process, called classical diffusion, is not normally regarded as a serious cause of leakage because at the high temperatures required for fusion the rate of collision between ions and electrons is very low. Furthermore, the rate of escape of plasma by classical diffusion is inversely proportional to the square of the magnetic-field strength, so that the loss of plasma through this route can be greatly diminished by using a strong magnetic field.

Both the ions and the electrons can still move freely along the lines of force, however, and in order to make a magnetic bottle work one must prevent the plasma from streaming out the ends. There are two principal ways to do this, and almost all magnetic bottles fall into one of these two categories. One is the open-end, or "mirror," device; the other is the closed, or toroidal, device [*see illustration on page 78*]. In a mirror device the magnetic field is made stronger near the end walls, so that most of the particles are reflected back into the interior of the bottle and hence cannot lose their energy to the end walls. In a toroidal device the lines of force are simply bent into closed loops and given a slight twist.

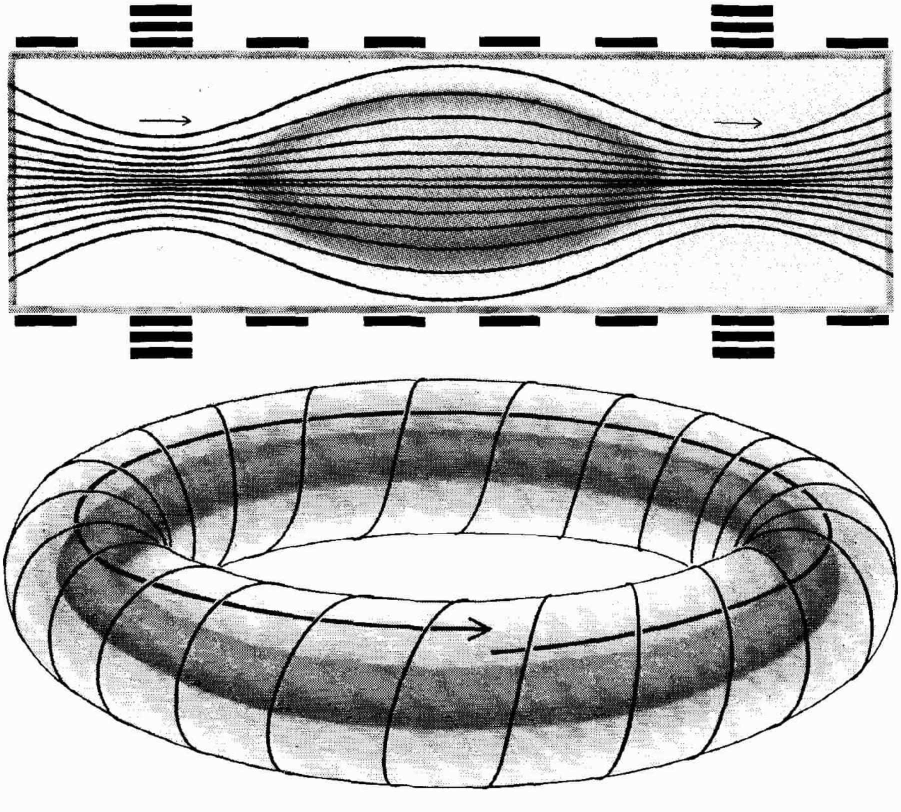
As they stand, these simple magnetic bottles will hold individual charged particles but will not hold a plasma. This is because a plasma behaves more like a fluid than like a bunch of individual particles. A useful analogy here is an invert-



MODEL C STELLARATOR is the latest and largest in the stellarator series of plasma-confinement devices built at the Plasma Physics Laboratory (formerly Project Matterhorn) of Princeton University. The stellarators are in the shape of a torus, or doughnut, at the center of which the plasma is confined by means of an elaborately "sheared," or twisted, magnetic field. The sheared field eliminates a class of plasma instability predicted by magnetohydrodynamic, or hydrodynamic, theory. The toroidal plasma vessel of the Model C has an inside diameter of eight inches and an axial length of 40 feet. It is obscured by the large confining-magnet coils.



SMALLER EXPERIMENTAL DEVICE, called the reflex-arc, or L-2, machine, was built by the author at Princeton to investigate the cause or causes of the "anomalous diffusion," or radial leakage, of plasma that occurs in every "magnetic bottle" built so far. The L-2 is typical of a number of comparatively small-scale experimental devices that have a linear rather than a toroidal geometry. Electrons emitted from hot cathodes at each end of the machine ionize a low-pressure gas in the central chamber. The entire chamber serves as an anode. The circular magnet coils set up a straight magnetic field that is parallel to the axis of the plasma chamber.



TWO APPROACHES can be used to prevent a plasma (*color*) from streaming out the ends of a magnetic bottle. One is the open-end, or "mirror," device (*top*), in which the magnetic field (*black lines*) is made stronger near the end walls, reflecting most of the particles back into the interior of the bottle. The other is the closed, or toroidal, device (*bottom*), in which the lines of force are simply bent into closed loops and given a slight twist. As they stand, these simple magnetic bottles will hold individual charged particles but will not hold a plasma, which behaves more like a fluid than like a bunch of individual particles.

ed beaker of water [*see upper illustration on page 80*]. If a leakproof and frictionless piston separated the water from the air below it, the water would be held up by the pressure of the air and would not fall out of the beaker. If the piston were removed, small ripples could develop on the surface of the water. Such a ripple would be unstable, because there would be less water pushing down on the trough of the inverted ripple than on the crest. The trough would be pushed upward and the crest would fall downward. The ripple would then grow into a wave, and of course the water would promptly fall out of the beaker. In general this process will occur whenever a light fluid (in this case air) supports a heavy fluid (water).

In a plasma the light fluid is the magnetic field and the heavy fluid is the plasma. Although real gravity is negligible here, there is an effective gravitational force due to a centrifugal effect whenever the lines are curved. To grasp how an instability develops, imagine that the plasma boundary is idealized into a sharp transition between the plasma and the surrounding vacuum and is allowed to have a small ripple [*see lower illustration on page 80*]. When the gyrating particles are pushed by a gravitational or electric force, they drift in a direction perpendicular to the force. Since a gravitational force pushes downward on all the particles, the positively charged ions drift to the left and the negatively charged electrons to the right. This causes a positive charge to build up to the left of the plasma protuberances and a negative charge to the right. The electric field resulting from this separation of charge causes a drift downward where there was already a protuberance and upward where there was a fissure. The ripple grows in size until the plasma reaches the wall. This plasma analogue of the water falling out of the beaker is called in hydromagnetic theory a gravitational instability. It is also called a "flute" instability, because the unstable plasma is marshaled along the lines of force, making the ripples long and straight like the flutes of a Greek column.

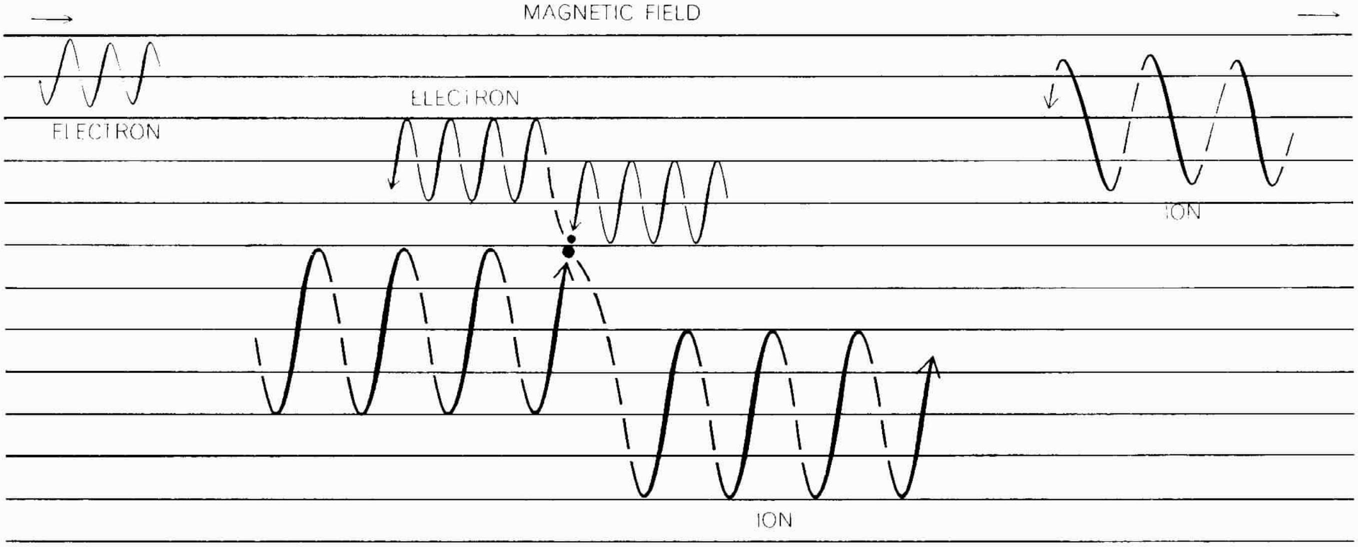
Ingenious methods have been devised to overcome flute instabilities. For instance, the magnetic-mirror device can be stabilized by adding four current-carrying rods that distort the magnetic field in such a way that the field is stronger everywhere outside the plasma than it is inside, thereby trapping the plasma in a kind of magnetic well. A flute instability cannot occur in such a situation. The toroidal device can be stabilized by giving the lines of force a twist that is larger near the walls than near the axis. This sheared magnetic field is the principle of the toroidal device called the stellarator [see "The Stellarator," by Lyman Spitzer, Jr.; SCIENTIFIC AMERICAN, October, 1958]. A flute perturbation following the lines of force on one surface no longer follows the lines on the next surface because these lines have shifted. It is as though the flute had become so confused and tangled up that it died out.

In spite of elaborate precautions to avoid flutes and other instabilities predicted by hydromagnetic theory, almost all magnetic bottles were found to leak at a rate some 1,000 times faster than that of classical diffusion. (An exception will be noted later.) At first it was thought that the methods used to heat the plasma—usually electric currents induced in the plasma itself—were the cause of the instabilities. In the stellarator, however, it was found that even when these currents were eliminated, anomalous diffusion was still present; the plasma simply refused to hold still in a magnetic field. Violent motions of the plasma were always observed, and for long time all such inexplicable behavio was lumped under the heading "cooperative phenomena." The plasma particles apparently cooperated with one another in some way, always managing to find a way to wiggle out of the magnetic bottle. The rate of loss was not only high but was also inversely proportional to the magnetic field rather than to the square of the magnetic field, as in the case of classical diffusion; this meant that increasing the strength of the magnetic field would not help as much.

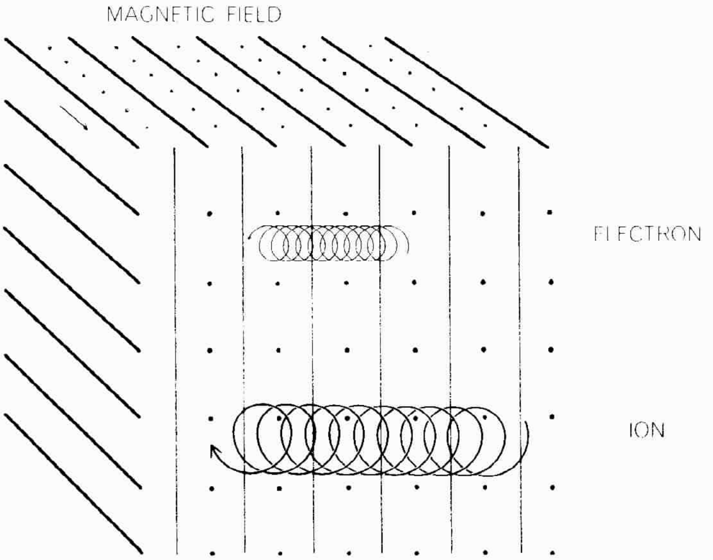
The inversely proportional, or linear, dependence of leakage on magnetic-field strength was reminiscent of an old puzzle in plasma physics called "Bohm diffusion." During World War II a group headed by David Bohm at the University of California at Berkeley, while working on the separation of isotopes by electric discharges in magnetic fields, discovered that the plasma created by an electric arc leaked across the magnetic field unexpectedly fast. Large-amplitude oscillations of the electric field were observed inside the arc, and Bohm surmised that these electric fields were the cause of th leakage. He worked out an equation th predicted that the rate of diffusion in the radial direction (at right angles to the axis of the magnetic field) was inversely proportional to the strength of the magnetic field. This gave a leakage much larger than classical diffusion would give and more in agreement with the experiment. Although it turned out later that the experiment was incorrectly interpreted, many subsequent experiments did approximately obey Bohm's equation, and plasma loss following such a law has been known ever since as Bohm diffusion.

No one (not even Bohm) has been able to give a complete proof of his equation, but if one disregards certain unexplained constants, it is possible to derive the linear dependence of Bohm diffusion from a simple argument involving the physical dimensions of two factors: the Larmor radius and the frequency at which the particles gyrate.

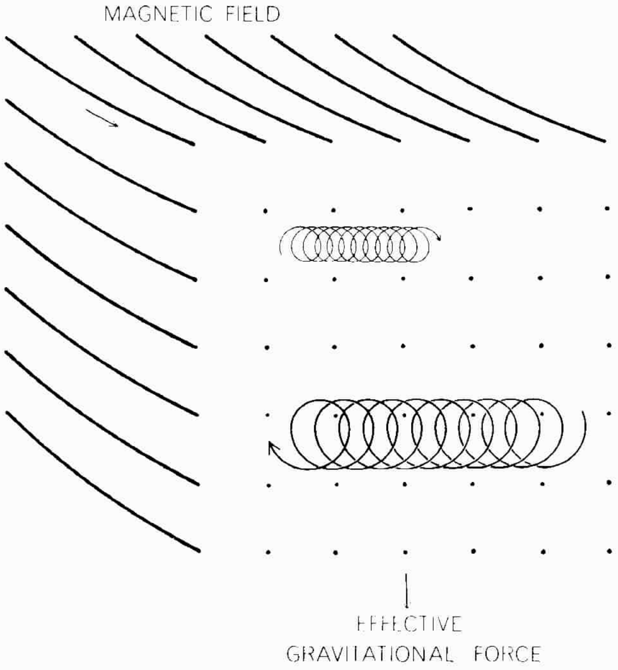
Interest in anomalous diffusion was revived by the fusion program, and in 1955 Albert Simon and Rodger V. Neidigh of



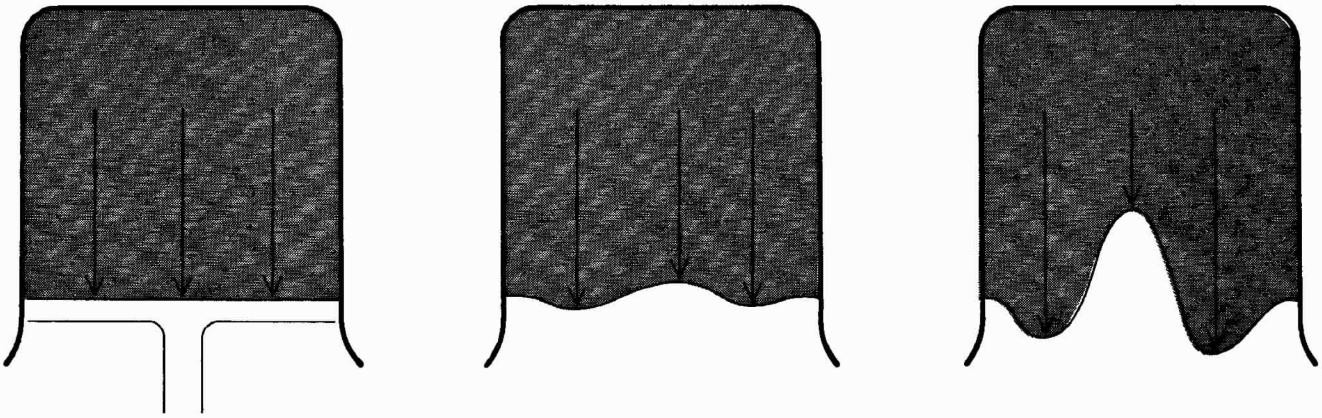
IN A MAGNETIC FIELD the positively charged ions and the negatively charged electrons that constitute a plasma gyrate in opposite directions around the magnetic lines of force. The Larmor radius, or radius of gyration, of the particles depends on their thermal velocity and mass. For a hydrogen ion this radius is about 40 times larger than it is for an electron of the same energy. When an ion and an electron collide (*center*), the "guiding center," or center of gyration, of each particle can jump to another line of force a Larmor radius away, on the average. By participating in a large number of collisions a particle can migrate across the field.



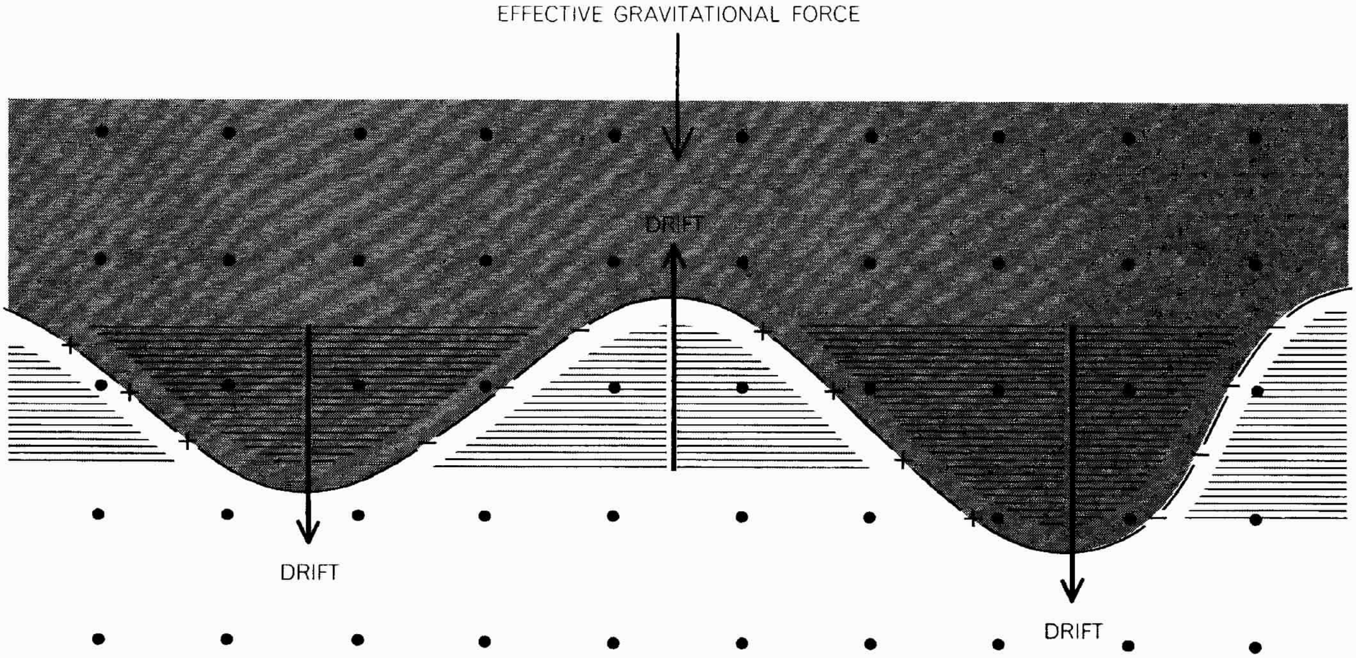
IN AN ELECTRIC FIELD that is at right angles to the magnetic field the charged particles in a plasma tend to drift in a direction that is at right angles to both fields. In the downward electric field shown here an ion drifts to the left; energy gained from the electric field during the downward part of each orbit gives the ion a larger Larmor radius at bottom than at top. An electron gyrates in the opposite sense, but the electric force acting on it is reversed because it is negatively charged, and it ends up drifting to the left also.



IN A CURVED MAGNETIC FIELD the charged particles in a plasma experience an effective gravitational force toward the outside of the curve. This force arises because as the particles move around the curve they tend to be thrown outward (in this case downward) by a centrifugal force. The effect of a downward gravitational force is to make an ion's guiding center drift to the left, gaining energy during the downward part of each orbit. An electron drifts to the right because its gyration is in the opposite sense.



INVERTED-BEAKER ANALOGY is helpful in understanding the fluid behavior of plasma in a magnetic field. As long as a leakproof and frictionless piston separated the water in the beaker from the air below it, the water would be held up by the pressure of the air (*left*). If the piston were removed, small ripples could develop (*center*). Such a ripple would tend to grow, because there would be less water pushing down on the trough of the inverted ripple than on the crest, and the water would soon fall out of the beaker (*right*).



IDEALIZED RIPPLE at the boundary between a column of plasma (*top*) and the surrounding vacuum tends to grow under the influence of the effective gravitational force created by a curved magnetic field. (In this cross section the curved magnetic lines of force appear as black dots.) The gravitational force causes ions to drift to the left and electrons to the right, with the result that an excess positive charge accumulates on the left of each ripple and an excess negative charge on the right, while the bulk of the plasma remains neutral. This separation of charge produces an electric field (*colored lines*), which causes the plasma to drift in the direction of the heavy black arrows, enlarging the ripple. This type of plasma instability is called a gravitational, or "flute," instability.

the Oak Ridge National Laboratory decided to repeat the Berkeley experiment with more care. They found that the radial-diffusion coefficient was not inversely proportional to the magnetic field at all but to the square of the magnetic field, as in the case of classical diffusion. The magnitude of this coefficient, however, was much larger than it is for classical diffusion. Simon correctly explained this discrepancy by noting that the plasma was not long enough to be considered infinitely long; when he calculated the effect of the electrically conducting end plates, he found he could explain the plasma loss rate without invoking either electric-field oscillations or anomalous diffusion.

This discovery triggered a large number of experiments both in this country and abroad in which the end plates were removed by either placing them far away or replacing them with insulators. These experiments were done in partially ionized gases, in which neutral atoms are present along with ions and electrons. Diffusion in such gases is somewhat different from what it is in fully ionized gases. In fully ionized gases ions and electrons diffuse out at the same rate, because they collide with each other and their momentum is conserved. In partially ionized gases ions and electrons diffuse out separately by colliding with neutral atoms. Since electrons have smaller Larmor radii and therefore take smaller steps, they diffuse out slower than ions. The ions leave behind a negative space charge, which creates an electric field, which in turn holds the ions back. It is the short-circuiting of this electric field by the metallic end plates that Simon used to explain the arc experiments.

The conclusion drawn from the later experiments is that no anomalous diffusion is needed to explain the loss rate of ions, although something extra may be needed to help drain out the slowly diffusing electrons. A possible exception to this generalization may have been observed in the recent experiments of V. E. Golant and his colleagues in the U.S.S.R. They studied the decay of a plasma in long, thin tubes such that the end plates can make no difference [*see lower illustration at right*]. They found that if the tube radius was small enough, the diffusion could not be entirely explained by collisions alone. This finding strongly suggested the existence of as yet undiscovered instabilities in the partially ionized plasma.

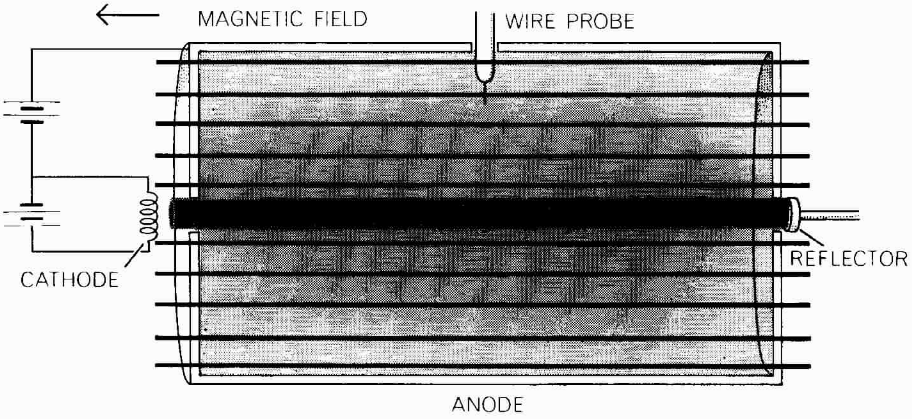
What do these experiments in partially ionized gases have to do with those in fully ionized plasmas, in which the loss rate is definitely anomalous? In stellarators, for instance, diffusion is generally found to obey Bohm's equation, provided that a somewhat different constant is used. Why has Bohm's equation come into the picture even though it is not needed for its original purpose? Are the observed oscillations actually related to Bohm diffusion? In order to answer these questions physicists began to look beyond the macroscopic decay of a plasma at the microscopic behavior of the plasma's fluctuations.

The results of one such investigation, carried out in 1961 by my colleagues and me at the Plasma Physics Laboratory of Princeton University, are shown at the top of the next page. The oscilloscope traces represent the signals picked up by a Langmuir probe, a small wire used to detect the local value of the plasma density or the electric potential. The top trace was obtained from the fully ionized plasma in a stellarator; the bottom trace was from the partially ionized plasma in a device called a reflex arc [*see bottom illustration on page 77*]. In spite of the great difference in the role played by the neutral atoms in the diffusion process, the two traces look very much alike. The oscillations seem quite random, but a single frequency predominates, usually in the range from 20 to 50 kilocycles.

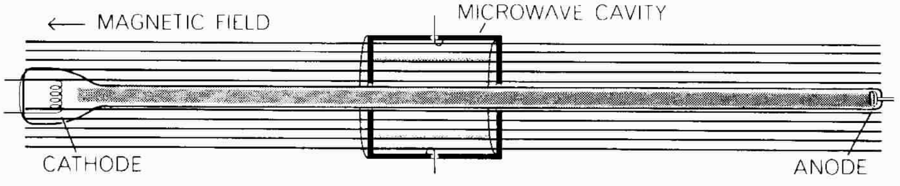
When the frequency content of these signals was analyzed, we found in each case a frequency spectrum in which there is indeed a continuum of frequencies, with a broad peak at the dominant frequency. The surprising thing about these spectra is that the power is concentrated at such low frequencies, well below any of the natural frequencies of the plasma. At the time only one type of oscillation was known to have such low frequencies: an ion-acoustic wave, the plasma analogue of an ordinary sound wave. Ion-acoustic waves, however, can exist at all frequencies up to a certain maximum, which for these experiments was an order of magnitude higher than the frequencies we were observing. If these were ion waves, it seemed strange that they should be limited to frequencies well below their natural maximum. To test the ion-wave hypothesis, Alfred W. M. Cooper and I measured the phase velocity of the waves by aligning two movable probes along the same line of force and using correlation techniques to pull out the parallel wavelength at each frequency amid the jumble of frequencies. The wave velocity turned out to be about an order of magnitude higher than the ion-wave velocity. This seemed to rule out ion waves, at least for the partially ionized plasma.

Other possibilities were examined, but none would fit even the crudest piece of data: the predominance of frequencies in the 20-to-50-kilocycle range. The trouble was that up to that time almost all plasma theory was concerned with homogeneous plasmas—plasmas with the same density everywhere. Confined plasmas, however, necessarily have an edge, so that somewhere there must be a slope of density, and the plasma is not homogeneous. When plasma theory was extended to inhomogeneous plasmas, a class of low-frequency waves called drift waves became a factor.

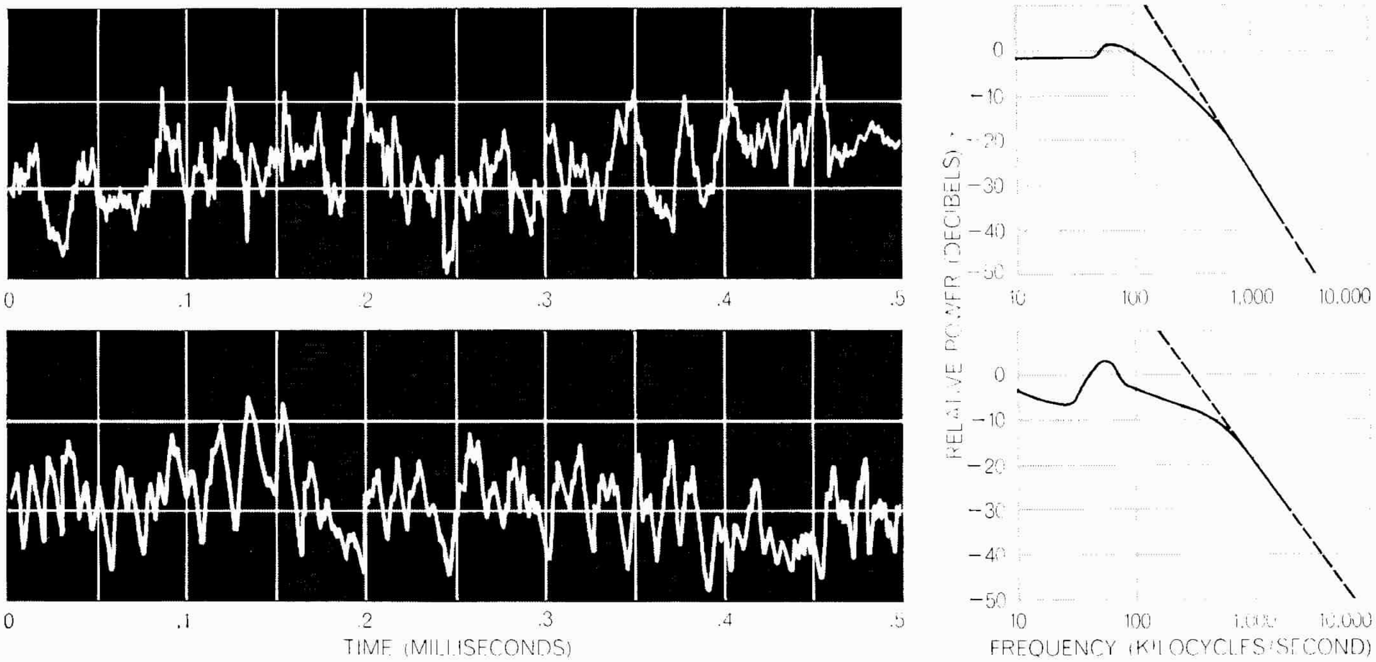
The discovery of drift waves can perhaps be traced to an experiment performed in 1960 by B. Lehnert and F. C. Hoh at the Royal Institute of Technology



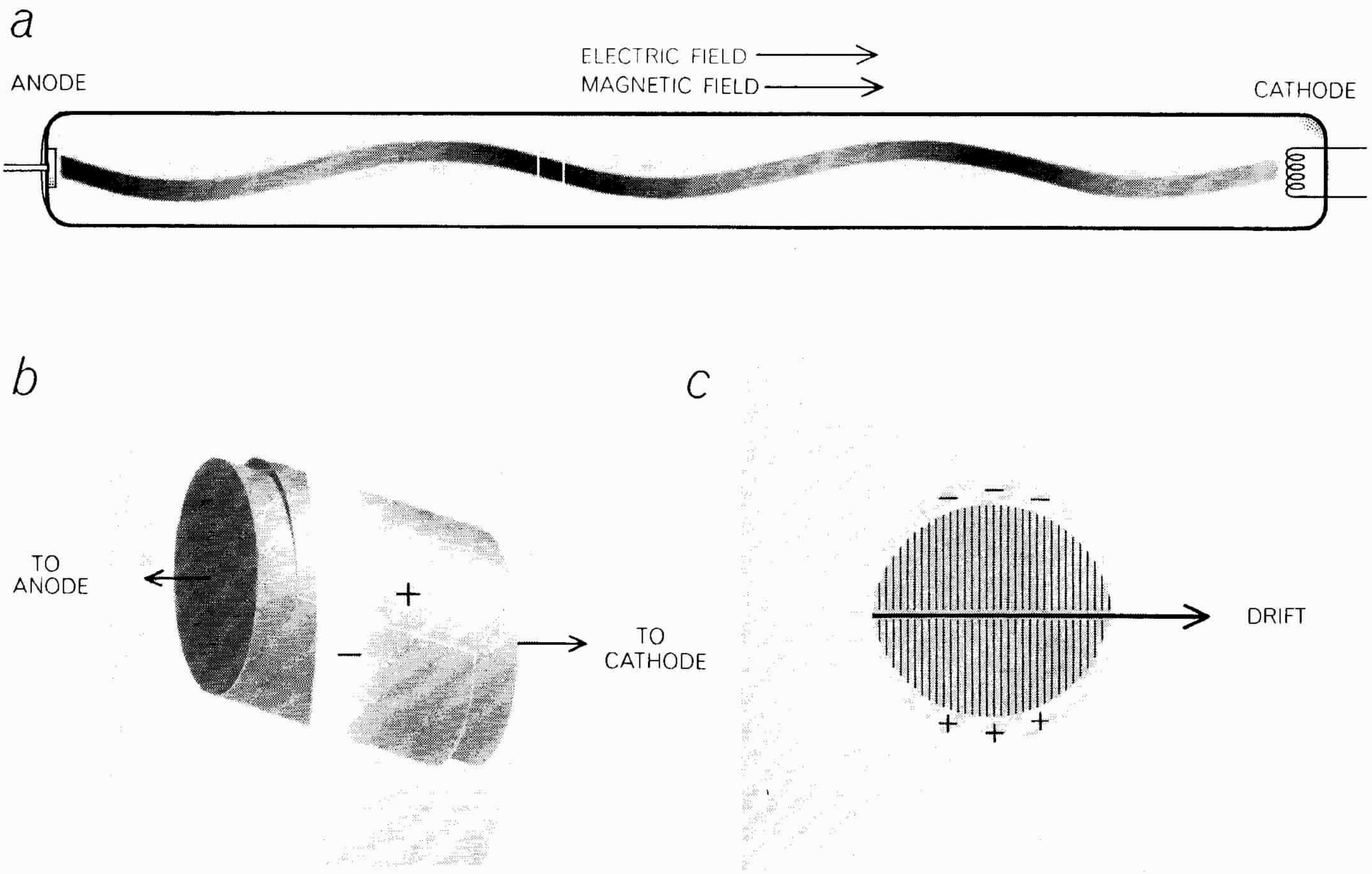
ELECTRIC-ARC EXPERIMENT was first performed during World War II by a group under David Bohm at the University of California at Berkeley and was later repeated by Albert Simon and Rodger V. Neidigh of the Oak Ridge National Laboratory. The original experiment led Bohm to formulate an equation for the fast diffusion of a partially ionized gas across a magnetic field. The equation for "Bohm diffusion" predicts that the rate of diffusion in the radial direction is inversely proportional to the strength of the magnetic field. Electrons emitted by a hot filament (*left*) were drawn into a metal chamber (*center*) by an applied voltage, ionizing the gas in the chamber and forming a plasma column. The plasma diffused outward across the magnetic field by colliding with neutral gas atoms. A wire probe (*top*) was used to measure the local density and hence the rate of diffusion. Later experiments, including the one shown here by Simon and Neidigh, showed that the Bohm experiment was incorrectly interpreted but also turned up evidence of leakage that followed Bohm's equation.



FURTHER EVIDENCE of anomalous diffusion in a partially ionized plasma may have been observed recently by V. E. Golant and his colleagues in the U.S.S.R. They studied the decay of a plasma in long, thin tubes, thereby eliminating the possible effects of the end plates. The plasma was created by a gas discharge, as in the electric-arc experiment; the rate of diffusion was measured by the change in the resonant frequency of a microwave cavity (*center*). They found that if the tube radius was small enough, the diffusion could not be explained by collisions alone. This suggested the existence of unknown instabilities.



OSCILLATIONS in the density of plasma during diffusion were observed by means of a wire probe in two quite dissimilar devices: a stellarator (*top trace*), in which the plasma is fully ionized, and a reflex arc (*bottom trace*), in which the plasma is partially ionized. The oscillations in both cases are quite random, with a single dominant frequency, usually in the range from 20 to 50 kilocycles. A frequency analysis of the signals (*graphs at right*) revealed that the power was concentrated at unexpectedly low frequencies.



CORKSCREW INSTABILITY was first observed in 1960 by B. Lehnert and F. C. Hoh at the Royal Institute of Technology in Stockholm. In their experiment a weakly ionized plasma was created by an electric field parallel to both the magnetic field and the axis of the tube (*top*). When the magnetic field was increased, a helical filament, or corkscrew, of dense plasma arose and grew outward until it reached the wall of the tube. The ions in the corkscrew were pushed to the right by the electric field and the electrons to the left (*bottom left*). In a typical cross section of the filament (*bottom right*) the longitudinal shift of the ion corkscrew with respect to the electron corkscrew produced an excess of ions (*plus signs*) on one side and an excess of electrons (*minus signs*) on the other. This separation of charge resulted in a transverse electric field (*colored lines*), which caused the plasma to drift in the direction of the heavy black arrow. This drift is always in the outward direction, so that the corkscrew expands, carrying plasma to the wall of the tube.

in Stockholm. They studied the effect of a magnetic field on the most familiar of all plasmas, the "positive column." This is a weakly ionized discharge not unlike the one in an ordinary fluorescent lamp. Diffusion of plasma to the wall of the long glass tube followed the classical pattern up to a critical field around 1,000 gauss, beyond which violent oscillations appeared and anomalous diffusion set in. After seeing the Lehnert-Hoh results Boris B. Kadomtsev and A. V. Nedospasov of the Kurchatov Institute of Technology in Moscow produced a theory in 1960 that accurately predicted the value of the critical field and even the rate of anomalous diffusion slightly beyond the critical field. The mechanism of the instability that arises at large fields was later clarified by Hoh [*see bottom illustration on opposite page*].

Suppose a filament of plasma in the shape of a corkscrew suddenly becomes denser than the rest of the plasma. The electric field in the positive column tends to pull the ions in the corkscrew toward the anode and the electrons toward the cathode. The ion corkscrew then becomes displaced from the electron corkscrew by a longitudinal shift. At each cross section this shift causes an excess of ions on one side and of electrons on the other, giving rise to a transverse electric field. The field causes the ions and electrons to drift together, and as a result the corkscrew rotates. More important, if the corkscrew is twisted in the right direction with respect to the magnetic field, the drift brings in more plasma from the dense core of the column and the small perturbation grows denser. It also moves radially outward, causing an anomalously fast loss to the walls. In a subsequent experiment at the University of California at Berkeley, G. A. Paulikas, Robert V. Pyle and T. K. Allen confirmed the existence of such a corkscrew and were actually able to watch it grow. The velocity and direction of rotation and the sense of pitch of the corkscrew all fitted the theory. This mechanism does not work at magnetic fields lower than the critical field, because the gyration frequencies become so low that collisions with neutral atoms disrupt the electric-field drifts, even for the electrons.

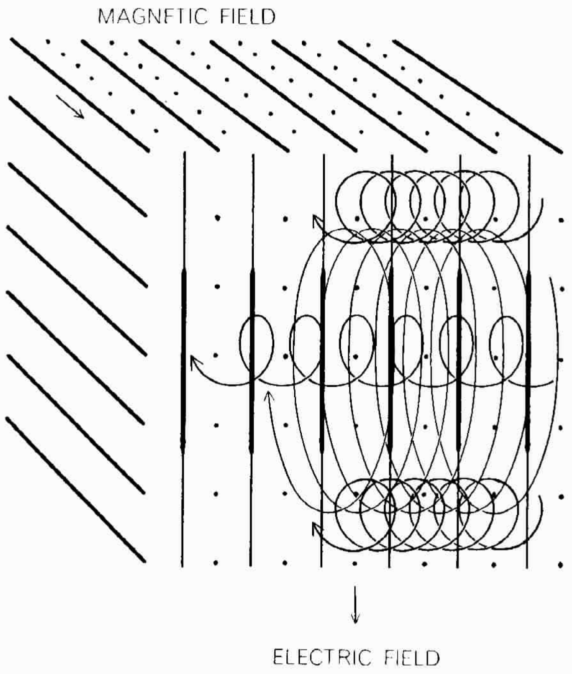
Here, then, was a case in which anomalous diffusion was definitely connected with an unstable oscillation, and the agreement between theory and experiment was as good as could be expected. The explanation of Kadomtsev and Nedospasov would work only for weakly ionized gases, however, not for the fully ionized gases needed for fusion. Physicists began to look for ways in which a fully ionized plasma could develop perturbations that were not straight flutes but were slightly inclined to the magnetic field, like the corkscrew. It was about this time that Marshall N. Rosenbluth of the University of California at San Diego first proposed a mechanism of anomalous diffusion based on the effects of the Larmor radii of the gyrating particles. Taking his lead, a group of Russian theorists then worked out a comprehensive theory of anomalous diffusion in which the plasma inhomogeneity, the Larmor-radius effects and the inclination of the flutes all play essential roles. Between 1961 and 1965 an avalanche of papers on the subject by numerous Russian authors appeared. This theoretical work was backed up in 1962, when N. D'Angelo and R. W. Motley at Princeton were the first to detect an isolated drift wave, in a low-temperature plasma of cesium ions.

To understand the difference between the new theory of microinstabilities and hydromagnetic theory, it is necessary to look a little more closely at the motion of charged particles in crossed electric and magnetic fields. Hydromagnetic theory predicts that the guiding centers of ions and electrons will drift with exactly the same velocity in a direction perpendicular to both the electric field and the magnetic field, even though the gyration of the ions is in the opposite sense to that of the electrons and the Larmor radius is much larger. This is strictly true, however, only if both fields are constant and uniform, or if the masses of the ions and electrons are both infinitely small. If the electric field varies in space or time, the finite mass of the ions will affect their drift velocity. Suppose the electric field varies in space and the magnetic field is uniform [*see illustration at top left on next page*]. Then ions with small Larmor radii (small thermal velocities) will drift faster in regions of strong electric field and slower in regions of weak electric field. An ion with a large Larmor radius, however, will spend part of its time in regions of electric field weaker than where its guiding center is. This is true even if the guiding center is not located at the point of strongest electric field. Accordingly in spatially varying electric fields ions will drift slower than electrons, because of their larger mass and larger Larmor radius.

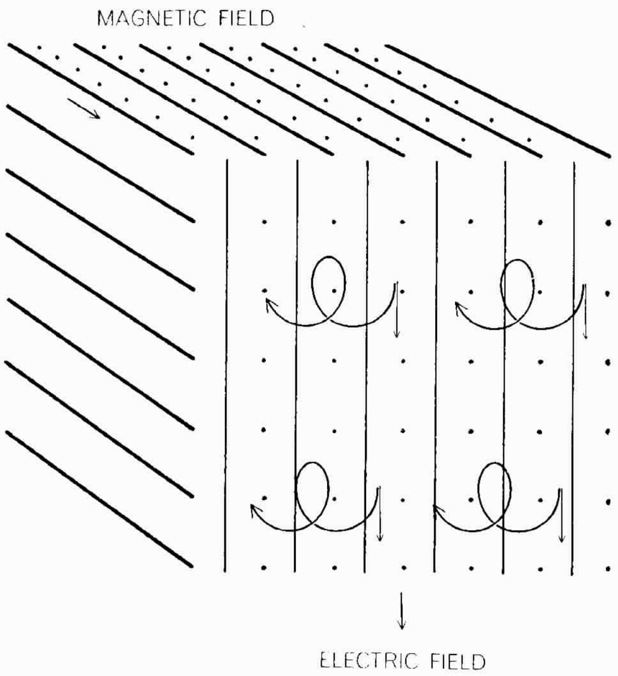
Suppose now that the electric field is uniform but fluctuates [*see illustration at top right on next page*]. Then it is the inertia of the ions that affects their drift. When an electric field is suddenly switched on, the ions that are at rest initially will, because of their inertia, be accelerated in the direction of the electric field rather slowly. Only after they have gained sufficient velocity will they begin to move in the direction perpendicular to the electric field. In this case the velocity of the guiding center has, in addition to its usual perpendicular component, an additional component in the direction of the electric field, gained during the first half-gyration. If the field is applied gradually, the parallel component is smaller but must still be taken into account. Electrons are accelerated very quickly by the electric field, and for them the parallel component due to inertia can be neglected.

When Rosenbluth took into account these two effects—the Larmor radius and the inertia of the ions—in his treatment of the gravitational flute instability, he found that the ripples traveled laterally across the magnetic field as they grew and that their growth rate was smaller than in hydromagnetic theory. Furthermore, if the ripples had a short enough wavelength, they would not grow at all; the instability would be stabilized by the Larmor-radius effect. If the flutelike ripples were not aligned along the magnetic lines of force but were at a slight angle to them, however, the instability would always arise, even for short wavelengths, as long as the wavelength was longer than the Larmor radius. Surprisingly, if one could now remove the gravitational field, unstable ripples would still grow. The same Larmor-radius effect that stabilizes straight-flute perturbations can cause instabilities of inclined, or helical, flutes. Because such instabilities need no driving force other than the ever-present pressure gradient in a confined plasma, they have been named "universal" instabilities.

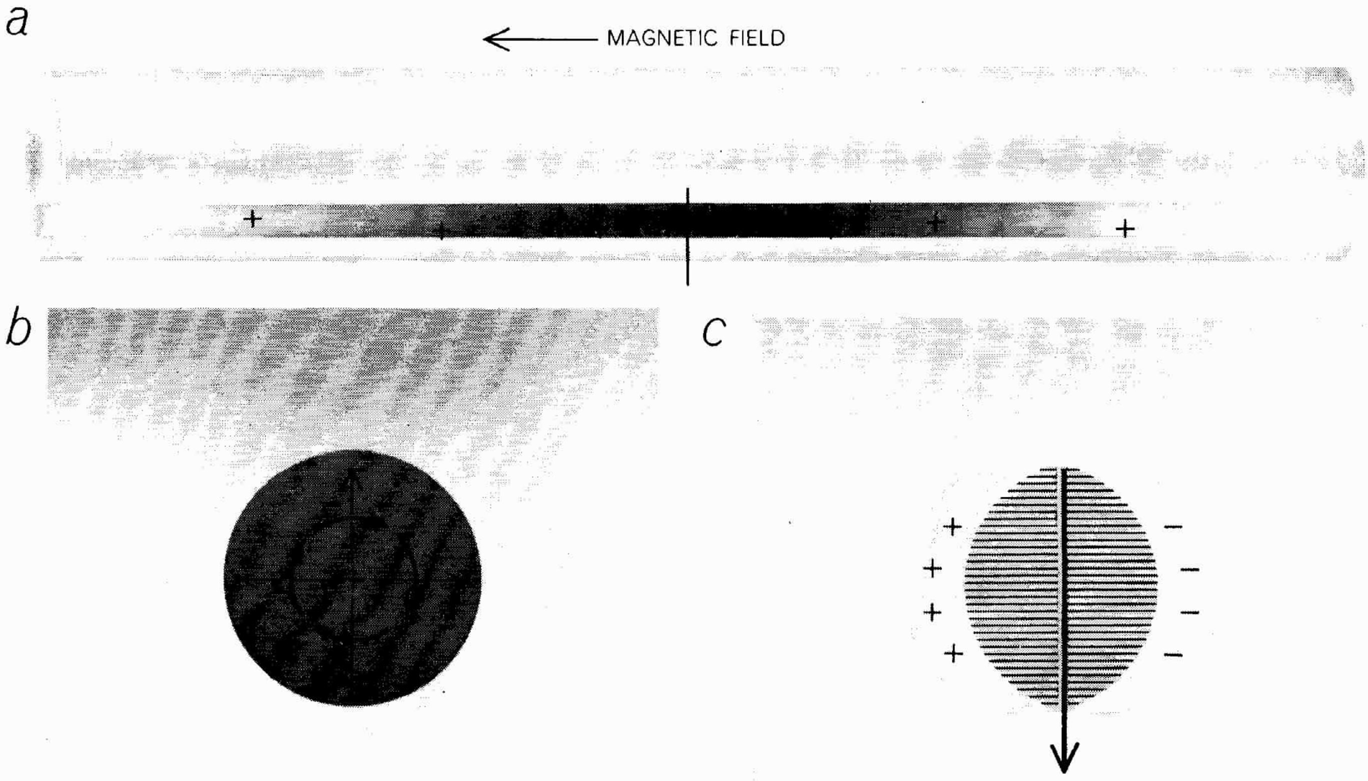
It is not difficult to see why such an instability should arise. Suppose in a uniform magnetic field one has a long column of plasma that is denser near the axis than it is near the edge [*see bottom illustration on next page*]. In the course of random thermal fluctuations of the plasma it is possible for plasma to accumulate sometimes into a long, thin filament of higher than average density. Let the filament have a length L and last for a time T. The filament must be so long that ions cannot travel the length L in a time T or the filament would be wiped out as soon as it started to form. Thus the thermal velocity of the ions is assumed to be much smaller than the ratio L/T. The thermal velocity of the electrons, on the other hand, is usually so large that it is much larger than any



LARMOR-RADIUS EFFECT influences the drift velocity of ions when the electric field (*color*) varies in space and the magnetic field (*black*) is uniform. Ions with small Larmor radii will drift faster in regions of strong electric field (*center*) and slower in regions of weak electric field (*top and bottom*). An ion with a large Larmor radius will sample regions of different field strengths during each orbit and on the average will be slowed down. As a result ions will drift slower than electrons in spatially varying electric fields.



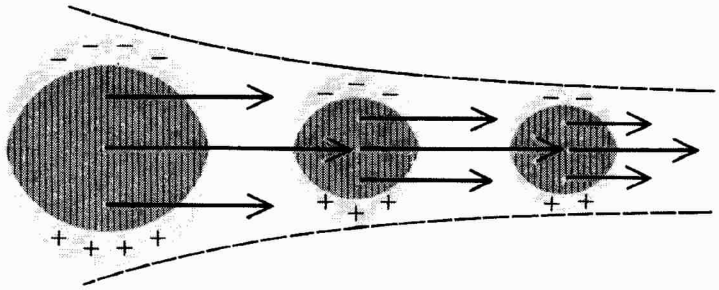
ION-INERTIA EFFECT becomes a factor in determining the drift velocity of ions when an electric field is suddenly switched on (a time-varying electric field). Then the ions that are at rest initially will, because of their inertia, be accelerated in the direction of the electric field (*short arrows*) before beginning to move in the direction perpendicular to the electric field. In this case the velocity of the guiding center has, in addition to its usual perpendicular component, an extra component in the direction of the electric field.



"UNIVERSAL" INSTABILITY needs no driving force other than the ever-present gradient in a confined plasma. Such an instability will occur whenever a long, denser-than-average filament of plasma can form within a general plasma background that is denser near the axis than it is near the edge (*a*). The higher pressure in the filament causes the electrons to move rapidly out the ends, leaving an excess positive charge near the center of the filament (*a, b*). This charge sets up a radial electric field (*colored arrows*), which causes the plasma to drift around the periphery of the filament (*black arrows*). Since the ions drift slower than the electrons (the Larmor-radius effect) and the background plasma is denser at the top of the filament than it is at the bottom, this difference in drift velocities causes excess positive and negative charges to build up on opposite sides of the filament (*c*). This new charge separation in turn creates a new electric field and hence a new perpendicular drift component, which is always outward. Hence the filament moves toward the wall.

reasonable value of L/T; therefore the electrons have time to move freely along the filament. Here one can consider the electrons as a fluid with regard to their motions along the magnetic field and neglect the motion of ions in this direction altogether. Now I want to show that once such a filament starts it will grow, conveying plasma toward the wall as it does so. It will be simpler to consider the Larmor-radius effect first without worrying about the inertia effect.

In a plasma the density of ions is everywhere nearly equal to the density of electrons, since a difference in charge densities of even one part in a million would lead to larger electric fields than the plasma could stand. At the center line of the long plasma filament this common density of ions and electrons is higher than elsewhere, so that a pressure gradient tends to push plasma along the magnetic field away from the center line. The ions, of course, do not have time to move at all, but the electrons start to move rapidly. As they do so they leave behind positive charges at the center line, and immediately an electric field is set up that impedes the electron motion and maintains the equality of charge densities. The balance of the pressure gradient and the electric forces on the electrons must be delicately maintained, since the electrons are so mobile. If one looks at a cross section of the plasma filament, it is clear that this accumulation of positive charges also gives rise to an electric field pointing outward from the axis of the filament. This in turn causes the ions and electrons to drift together around the periphery. Because of the Larmor-radius effect, the ions drift somewhat slower than the electrons. This would not cause any trouble if the plasma were homogeneous, but remember that the filament is superposed on a smooth slope of density from the center of the plasma column to the edge. As a result, when the drift proceeds from a region of high density to one of low density, more electrons than ions are brought in by the drift. Conversely, when the drift proceeds from a region of low density to one of high density, more ions are brought in. This results in an accumulation of positive and negative charges on opposite sides of the filament, creating an additional electric field. The additional field causes an additional drift, which is always in the outward direction. The plasma filament is unstable and grows because the outward drift brings denser plasma in from the surrounding plasma; this increases the density of the filament, thus further increasing the electric field and the outward drift. More important, the outward drift can automatically cause anomalous diffusion, because it is always in a direction such as to bring dense filaments of plasma away from the axis.



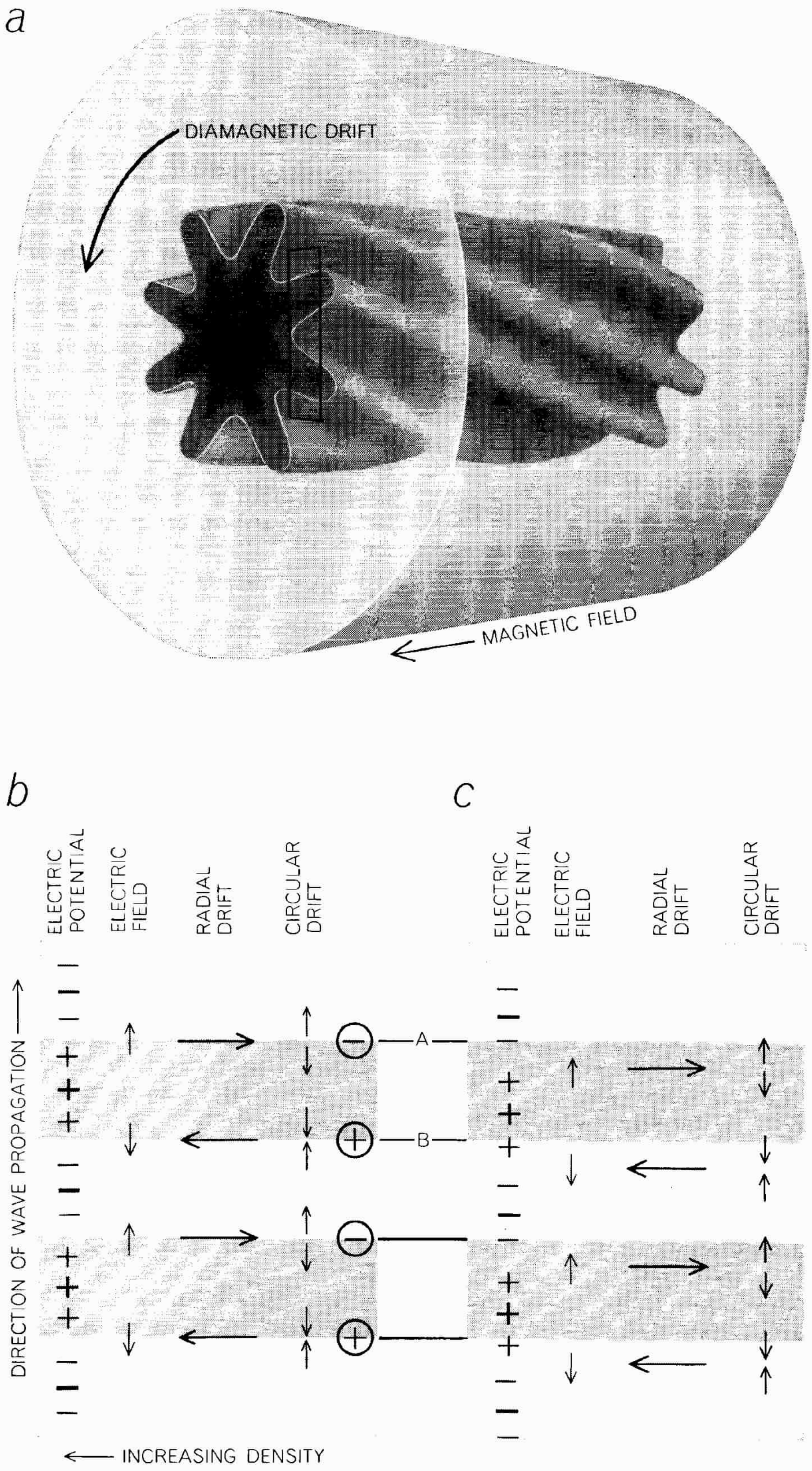
"CONVECTIVE CELL" might be created by a plasma filament that was moving outward to the chamber wall (*to the right*) under the influence of the electric field produced by the universal instability shown at the bottom of the opposite page. Successive layers of the filament would tend to get peeled off, since the electric field (*colored lines*) and hence the associated drift vectors (*heavy black arrows*) would be greater at the center of the filament.

In practice successive layers of the plasma filament would tend to get peeled off, since the electric field is strong at the center of the filament but weak in the regions of charge accumulation. This process might create an ever narrowing channel, in which plasma moves outward under the influence of the electric field [*see illustration above*]. Such a channel, called a "convective cell," could conceivably drain plasma to the wall steadily until the electric charges could somehow be dissipated.

I have glossed over a rather fundamental point in the interest of simplicity. If the electrons are so mobile, why do they not simply stream along the magnetic field to neutralize the charge separations that create the electric field? Indeed, if electrons were infinitely mobile, they would do just that, and the electric field would be vanishingly small. To get a universal instability, one must find a mechanism that limits electron mobility along the magnetic field. There are three such mechanisms: (1) collisions with ions, (2) electron inertia and (3) acceleration of resonating electrons by waves. The third mechanism is too complicated to explain here, but ironically it was the first one discovered and is known as *the* universal instability. For the last two mechanisms to be important, the length L must be very long—probably longer than can obtain in most experiments. In a stellarator, for instance, it is very likely the drag of electron-ion collisions that limits electron mobility along the magnetic field and allows the electric field to be finite.

The ion-inertia effect discussed earlier can also cause this instability. For the sake of simplicity let us now neglect the differential-drift effect discussed above, although in general both effects will occur together, and consider again a long cylinder of plasma with a gradual slope of density toward the edge [*see illustration on next page*]. A steady magnetic field but no electric field is applied. Imagine that the plasma develops a helical ripple with a wave motion proceeding circularly around the axis of the cylinder and with flutes at a slight angle to the magnetic lines of force. Let us look at a small section of this ripple—small enough so that the perturbed density does not change appreciably from left to right across the section. As before, the balance of forces on the electrons will require the electric potential to be positive where the perturbed density is high and negative where it is low. This gives rise to an electric field in the circular direction, which in turn causes both ions and electrons to drift in the radial direction. Note that this radial drift is to the right at point A, bringing in higher-density plasma, and to the left at B, bringing in lower-density plasma. A short time later, therefore, the density will be higher at A and lower at B. In other words, the ripple propagates counterclockwise in the cylinder. This propagation velocity is always in the same direction, and has nearly the same magnitude as what is called the electron diamagnetic drift velocity. Such waves are consequently known as drift waves.

As the wave passes by, the ions will "feel" an alternating electric field in the circular direction. Hence they will have a circular velocity component as well as the radial-drift one. The phase of the circular component is such that ions diverge from A and converge on B; thus an excess of positive charge builds up at B and an excess of negative charge builds up at A. Now, if one of the three electron-drag mechanisms listed above is operating, this charge buildup cannot be



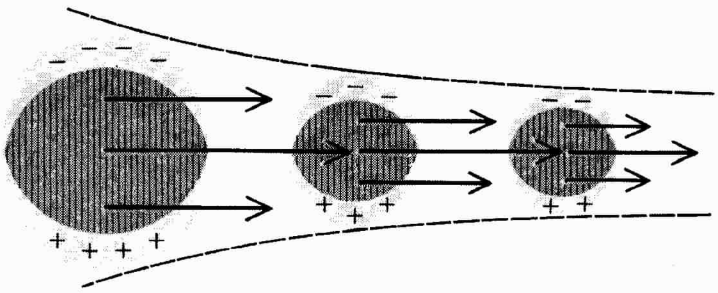
HELICAL FLUTE INSTABILITY is a type of universal instability that can arise as the result of the ion-inertia effect alone. The helical ripple actually occurs at all layers of the plasma column; it is shown here on only one level for the sake of clarity (*top*). In the small cross-sectional views of the ripple (*bottom*) the curvature of the column is neglected. The excess charges, associated electric fields and ion-drift components are given at bottom left for the case in which the resistivity of the plasma is zero. If the resistivity is finite, the accumulations of charge (*circled signs*) due to the circular drift component of the positive ions cannot be entirely dissipated and the charge distribution is shifted, as in the case at bottom right. This phase shift causes the drift wave to become unstable and to grow, carrying the plasma outward. It is possible to measure the phase shift experimentally.

entirely eliminated by electrons flowing rapidly along the magnetic field from trough to crest of the twisted flute. The potential at *A* will therefore be slightly negative and that at *B* slightly positive instead of zero as before. This has the effect of shifting the charge distribution downward, and of course the electric-field distribution and the radial-drift velocities shift with it. It is now clear that there is more plasma moving to the right where the ripple has a high density and less plasma moving to the left where the ripple has a low density; this brings in even more dense plasma. The ripple grows, and in so doing transports plasma away from the axis of the cylinder. The ion-inertia effect is what caused the phase shift between the charge and density distributions that made the wave unstable. This phase shift can be measured experimentally and can be used to determine if anomalous diffusion is associated with the growth of such waves.

The effect of ion inertia, then, is to make universal instabilities appear in the form of growing drift waves. The Larmor-radius effect does not change the oscillatory nature of the instability but merely adds to the growth rate. Drift waves will occur whenever electron mobility along the magnetic field is not perfect, provided that the plasma is long enough. The drift velocity is rather low, so that as the wave passes a stationary sensing probe a potential oscillating with a low frequency will be detected, in agreement with the observed oscillation. The dominant frequency corresponds to a ripple with a long wavelength.

It is a peculiarity of such drift waves that the plasma particles mainly oscillate back and forth in the radial direction, but the wave (that is, the density perturbation) propagates in the circular direction. The particles' motion can change the density only because of the background density gradient. This is the reason drift waves do not exist in homogeneous plasmas. In any plane perpendicular to the magnetic field the motion of the electron fluid is incompressible, but the motion of the ion fluid is compressible because of its inertia. A compressible motion and an incompressible motion are not compatible, however, if the densities of ions and electrons are to be maintained nearly equal to each other everywhere, as is necessary in a plasma. Hence a drift wave cannot exist at all unless either the ions or the electrons (actually the electrons) can move along the magnetic field to maintain equal charge densities. This is basically the reason the flutes are inclined to the lines of force:

reasonable value of L/T; therefore the electrons have time to move freely along the filament. Here one can consider the electrons as a fluid with regard to their motions along the magnetic field and neglect the motion of ions in this direction altogether. Now I want to show that once such a filament starts it will grow, conveying plasma toward the wall as it does so. It will be simpler to consider the Larmor-radius effect first without worrying about the inertia effect.



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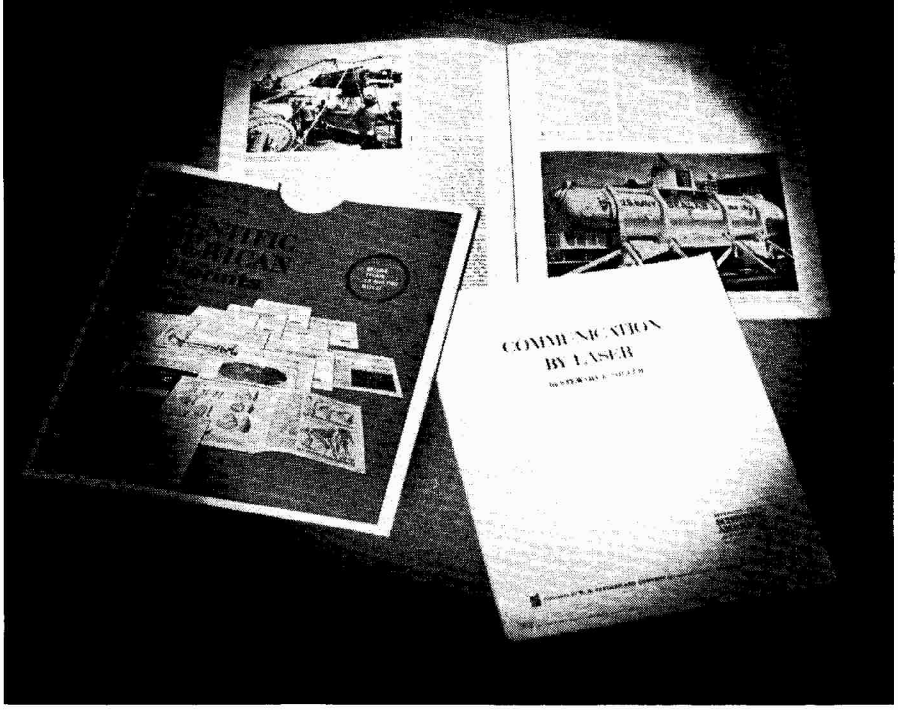
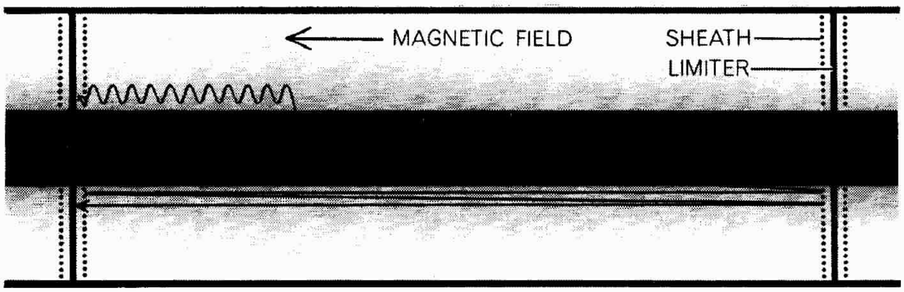
So far I have used the guiding-center description of particle motions in the directions perpendicular to the magnetic field but have regarded the electrons as a fluid for their motions parallel to the magnetic field. From experience this has been found to be the simplest way to explain the phenomenon, but is it compatible with viewing electrons as single particles in their parallel motions? Individual electrons zip along the lines of force so fast that they are subject to a rapidly oscillating electric field as they cross the helical flutes. Normally a rapid oscillation would leave an electron with a zero net displacement. In this case, however, the longitudinal electric field alternately accelerates and decelerates each electron in such a way that it spends more time in regions where the perpendicular electric field is making it drift outward and less time where it is drifting inward. Thus the electrons can drift outward on the average even in the single-particle picture.

The behavior of a single wave is clear enough, but many waves with different wavelengths can grow simultaneously, and as they become large they can mix with one another and give rise to the observed continuous spectrum of frequencies. The plasma is then in a state of electrostatic turbulence, which is very difficult to treat theoretically. Questions that remain unanswered include: What should the shape of the spectrum be? Does this shape depend on which of the microinstabilities is causing the turbulence? Do small eddies coalesce into large eddies, or do large eddies break up into small eddies as they do in ordinary gases? Does the turbulent state automatically lead to Bohm diffusion?

One thing is clear, and that is that plasma confinement will depend on the end plate conditions, as it did in the original arc experiment of Bohm's group. I alluded previously to an exception to the rule that all magnetic bottles leak. In some mirror devices exceptional stability has been observed, even when no precaution was taken to eliminate the simple gravitational instability. It has recently become clear that this stability is due to an effect involving the end plates of the mirror device. The plates are conducting, but the trapped hot plasma is not in contact with them. In the process of making a hot plasma, however, a cold plasma is produced incidentally; such a cold plasma is not well confined by the mirror device because its collision rate





BOUNDARY of a toroidal plasma is usually formed by an aperture-limiter, which is simply a plate with a hole in it. In this view the torus has been straightened out to show the interior and exterior regions created by the limiter. Plasma can be brought to the edge of the interior region by oscillations. Once it reaches the exterior region, it can flow easily along the magnetic lines of force to the limiter, where it is "scraped off." The "sheath," or thin boundary layer, surrounding the limiter repels electrons, causing them to bounce back and forth many times before they are lost to the limiter. This effect allows the ions and the electrons to depart at equal rates, leaving the plasma neutral, in spite of the higher velocity of the electrons. The small gyrations of the electrons have been omitted here for clarity.

is too high and particles can scatter through the magnetic mirrors. Charge fluctuations that tend to build up in the hot plasma can be short-circuited by currents flowing in the cold plasma along the lines of force to the conducting plates. Even when the end plates are insulators, the cold plasma may be dense enough to be a reservoir of charges sufficient to damp out the oscillations. Here the hot plasma is stable against straight-flute perturbations, and the machine is too short to allow drift instabilities. Unfortunately cold-plasma stabilization cannot be used in a working fusion reactor, because at the high densities needed the cold plasma would be quickly heated up.

In toroidal devices such as the stellarator there are no end plates, but it is necessary to take into account a boundary imposed by a plate with a hole in it that establishes the diameter of the plasma [*see illustration above*]. Instabilities inside the plasma can easily bring particles up to the edge of the hole in growing waves by means of the circular electric field. Beyond the hole the fluctuating electric fields are short-circuited by the plate, and only small fields can exist because of the finite conductivity of both the plasma there and the "sheath," or thin boundary layer, surrounding the plate. Once a particle reaches the edge of the hole it is swept outside during the next cycle and then streams easily along the magnetic field to the plate, where it recombines with a particle of opposite charge. There is competition between the growth of a wave and its damping by the scraping off of plasma at the edge of the hole, so that an oscillation detected by a probe can seem to be a steady one. Clearly the loss rate can depend on the geometry of the perforated plate and the region outside the plasma, and it is not surprising that the measured coefficient in Bohm's equation varies in different experiments. Another way to view anomalous diffusion is to consider that drift instabilities grow until they have destroyed the density gradient that feeds them. This leaves a very steep gradient at the edge of the hole, across which the plasma can diffuse by classical processes at a fast rate.

There is one type of plasma generator in which the end effects are particularly simple and well understood. This is the "*Q* machine" invented by N. Rynn of Princeton, in which a low-temperature plasma is produced between hot tungsten end plates by the ionization of a beam of cesium or potassium atoms. The magnetic field is straight, so that the plasma is not confined at the ends; instead the ions are replenished by ionization, and electrons are supplied by emission from the end plates. This electron emission also serves to short-circuit and thus suppress all flute instabilities. Since no currents or other destabilizing forces are needed to create the plasma, practically the only instabilities that can occur are drift waves. Recently H. Hendel of Princeton has succeeded in isolating and making precise measurements on a pure drift wave in a *Q* machine. Such experiments hold great promise of increasing our understanding of drift waves and anomalous diffusion, and indeed this line of research is being followed in many *Q* machines all over the world.

There are many other types of microinstability that may also be important; these generally are modifications of the same basic mechanisms that are at work when the magnetic field is curved or when the plasma temperature is not uniform. A common feature of all such microinstabilities is that the rotating-wave velocity is rather low. This at least explains the predominance of low frequencies in the observed spectrum of oscillations. We do not yet know, however, whether a continuous spectrum is necessary to produce anomalous diffusion or whether a single coherent wave will do. More important, we do not even know if drift waves are responsible for the observed loss rates. Although drift waves can in principle lead to increased losses, there may still be an unknown mechanism that is even more effective. Several recent experimental results have hinted that this may be the case. For example, perhaps steady-state or very low-frequency electric fields can set up convective cells in which the plasma is continuously drained to the walls. These and similar questions are scheduled to be topics of discussion at an International Symposium on Fluctuations and Diffusion in Plasmas, meeting in Princeton from June 26 through 30.

If it turns out that microinstabilities are important, what can be done about them? It is generally agreed that a new family of devices called "magnetic multipoles," invented by D. W. Kerst of the University of Wisconsin and T. Ohkawa of the general Atomics Division of the General Dynamics Corporation, have the best chance of overcoming such instabilities, because the lines of force in these machines are bent in such a way that long filamentary perturbations cannot occur. A multipole device called the spherator, invented by Shoichi Yoshikawa of Princeton, combines this feature with a large shear in the magnetic field. The first experiments with small multipoles have been encouraging. It will take a few years, however, to see how well the spherators and larger multipoles perform. It would be too much to expect that they will be stable against all types of fluctuations, but possibly those that remain will not be deleterious to plasma confinement.

Even if the instabilities discussed in this article are conquered at low densities, the dream of thermonuclear power cannot be realized until it is ascertained that no unknown phenomena occur at high densities. The low-density problem has to be solved in any case, however, because the density will be low at least near the edge of the plasma, and the understanding of anomalous diffusion at low densities must be regarded as a significant step forward.