High Pressure Tokamaks

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OAK RIDGE NATIONAL LABORATORY
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ABSTRACT

The successful development of the neutral beam injection method of heating tokamaks has opened up a new range of theoretically predicted phenomena to be explored. This article, intended for the nonspecialist, reviews the existing experimental observations and theoretical understanding of tokamak equilibrium and large scale stability. Then a survey is presented of the new phenomena, such as flux conserving sequences of equilibria and pressure-driven ballooning modes, that are expected to accompany the significantly enhanced plasma pressure to be produced in tokamaks now under construction.

1. INTRODUCTION

The objective of the controlled thermonuclear fusion program is to heat a gas composed of light elements to a temperature considerably hotter than the center of the sun and to confine this hot plasma long enough for the resulting nuclear reactions to produce more energy than was consumed. If a mixture of deuterium and tritium is used, for example, at a temperature of 6 keV (69.63 Million degrees K) and a particle density of 4×10^{14} ions/cm^3, the plasma energy must be confined for at least 2 seconds in order to produce a useful amount of nuclear energy. Other fuels would require higher ignition temperatures. While the challenge of producing these conditions in the laboratory is great, the reward is enormous. Thermonuclear fusion within the sun is ultimately the source for almost all of the energy used by mankind so far. Thermonuclear fusion on earth is a fundamentally new source of energy which should ultimately become the most important means of producing electrical power. It is only a question of time before fusion becomes a useful and attractive energy alternative.

Tokamaks are now a leading contender among the devices being built to confine hot plasmas for controlled thermonuclear fusion. Essentially, a tokamak is a large transformer in which the toroidally shaped (doughnut shaped) plasma serves as the secondary winding. The current driven through the plasma creates a magnetic field that confines the plasma pressure and provides thermal insulation. In addition, this current heats the plasma up to a maximum temperature of a few keV (not quite hot enough for ignition). Until recently, resistive heating by this toroidal current was relied on almost exclusively to heat the plasma. Now, however, there is a revolution in the design and capability of tokamaks with the advent of a very successful form of auxiliary heating called neutral beam injection. To produce this beam, an electrical discharge is used to ionize the gas in a separate chamber. The positive ions are then electrically pulled out and accelerated by a potential of 40,000 V or more. As these ions pass through a second chamber filled with gas at low pressure, they pick up electrons and proceed into the tokamak as energetic neutral atoms. These neutral atoms pass freely through the magnetic field that confines the tokamak plasma. They penetrate into the plasma and exchange electrons with the plasma ions to form a beam of fast ions within the plasma. This ion beam then slows down by Coulomb collisions and imparts its energy to the rest of the plasma.

Recent experiments using neutral beam injection have indicated that the plasma temperature can be raised at will, with no adverse effects observed so far. With neutral beam injection systems now under construction, tokamaks should soon be capable of achieving and maintaining temperatures of thermonuclear interest (whereupon it remains to raise the energy density and confinement time sufficiently to produce useable amounts of energy).

As the plasma pressure is raised, computational studies have indicated that new kinds of equilibria must be produced to provide magnetic confinement. With the advent of powerful auxiliary heating, confinement is no longer inherently coupled to ohmic heating and a better test can be made of the existing energy confinement theories. Finally, theoretical predictions have indicated that an entirely new class of large scale instabilities, called ballooning modes, should set in as the plasma pressure is raised significantly. Studies have indicated ways of controlling these instabilities by adjusting the shape and profile of the plasma in order to achieve the maximum stable pressure. This article will survey some of these major developments in the tokamak approach to controlled thermonuclear fusion.

2. TOKAMAK STABILITY

The history of tokamaks has largely been a history of controlling large scale instabilities. A brief review of these instabilities will indicate many of the reasons why tokamaks are built the way they are; it will also provide some of the intuition needed to understand the new theoretical predictions for high pressure tokamaks.

Let us begin with the simplest case investigated in some of the experiments performed during the early 1950's in which the plasma was produced with only its self-generated poloidal magnetic field (wrapping the short way around the torus) and was found to be violently unstable. During this instability, parts of the plasma column constrict while other parts bulge out. The magnetic field around the constricted parts becomes stronger, since the toroidal current has to squeeze through a narrower channel there, and the stronger field exerts a greater inward radial force on the plasma which makes the column there constrict further. The plasma pinches off in the form of a sausage, generating a burst of high energy ions and terminating the discharge in the process.

This sausage instability can be stabilized completely by permeating the plasma with a toroidal magnetic field (the long way around) produced by solenoidal coils encircling the plasma around the torus. A combination of two mechanisms can be used to explain this stabilizing effect. First, a magnetic field may be thought of as being frozen into any electrically conducting fluid such as a hot plasma, in the sense that field lines may be thought of as having to move together with the fluid when the motion takes place on a time scale faster than resistive diffusion. (Actually, this interpretation is not unique, but any physical consequence derived from it is valid.) Second, any magnetic field may be thought of as exerting pressure perpendicular to the field lines and tension parallel to the field lines. Hence, the toroidal magnetic field is compressed as it constricts with the plasma, and the compressed field exerts a greater outward radial force which inhibits further constriction.

Once the sausage instability was suppressed, experiments revealed a second kind of instability in which the plasma column twists into a kink which looks like a corkscrew. As each segment of the column bends, the magnetic field that wraps around the column becomes stronger around the inner edge of the bend, where it is being squeezed through a shorter arc length, and weaker around the outer edge, where it is being stretched. The resulting magnetic pressure then pushes the column to bend further and rapidly drives the plasma into the wall.

By 1958, it was realized that this large scale kink instability could be suppressed by making the toroidal magnetic field strong enough and the plasma fat enough so that none of the magnetic field lines close upon themselves once aound the torus. This condition is known as the Kruskal-Shafranov stability criterion. Roughly speaking, if the product of toroidal magnetic field and minor radius is greater than the product of poloidal magnetic field and major radius, then the tension along the field lines prevents the column from bending into a kink. The Kruskal-Shafranov stability criterion is of overriding importance in the design and operation of tokamaks. It requires a strong toroidal magnetic field — much stronger than the poloidal magnetic field. Given the maximum toroidal field we can afford in any given device, it sets an upper limit on the toroidal current that can be driven through the plasma, and therefore, an upper limit on the resistive heating and pressure confinement provided by this current. Hence, the Kruskal-Shafranov stability criterion provides the motivation for building tokamaks with the smallest possible aspect ratio — a fat rather than a thin torus — even though a low aspect ratio creates a number of engineering problems.

Even after the kink instability is suppressed, at least three more large scale instabilities are observed in tokamak experiments. The most dramatic of these is called the disruptive instability. When it strikes at random times during the discharge, the plasma abruptly expands in minor radius, shifts inward in major radius, produces a voltage spike around the toroidal plasma column which kicks back against the transformer voltage, and finally, those electrons that have been accelerated to relatively high energies (called runaway electrons) suddenly strike the wall and thereby generate a pulse of hard X rays. A strong disruptive instability can terminate the plasma discharge and precautions must be taken to avoid damage to the wall from local concentrations of runaway electrons. Fortunately, the disruptive instability can be avoided altogether by operating tokamaks in the proper range of filling gas pressure, toroidal current, purity, etc. In effect, tokamaks operate on an island in parameter space. The range of these parameters can be extended by neutral beam injection and by puffing in additional gas during the discharge. Also, experiments on the Pulsator tokamak at the Max-Planck-Institut fur Plasmaphysik in Germany have shown that a moderate externally-applied helical magnetic field is found to delay the onset of a disruptive instability in an otherwise disruptive discharge. A disruptive instability is precipitated, however, when the helical applied field is too strong. It can also be induced if the plasma is poorly centered or if a probe is inserted into the plasma. All of these observations have been determined experimentally.

The physical mechanism for disruptive instabilities was a mystery for many years. It was difficult to make proper measurements inside the plasma on a phenomenon that occurred abruptly at random times, and it was equally difficult to think of any mechanism which could be triggered with little or no apparent change in the plasma state and yet have such a large effect on the behavior of the plasma. However, a theoretical scenario has been developed by a number of people over the last few years which roughly explains the sequence of observed phenomena and the approximate time scales. The central idea in this scenario is that a kind of instability, called a tearing mode, can cause the magnetic field to break up into thin filamentary structures, called magnetic islands, which twist through the plasma. When several magnetic islands with different helicity grow wide enough to overlap with each other, then at least some of the magnetic field lines can wander through the plasma column over some radial interval between the center and the edge. Since heat and fast electrons flow rapidly along field lines but slowly across the magnetic field, the onset of this magnetic field line reconnection suddenly allows the plasma temperature to spread and fast particles to be lost. Furthermore, eddy currents at the edges of the rapidly growing magnetic islands are believed to be responsible for the abrupt radial spread in plasma current (normal resistive diffusion takes much longer). The negative voltage spike and the inward shift of the plasma column then follow from an electrical circuit analysis of the instability following the current spread.

This scenario has been used to explain how a moderate externally applied helical magnetic field causes a delay in the onset of the disruptive instability. The applied helical field controls the width of the fundamental magnetic island (a magnetic island can be produced by any helically-resonant radial magnetic field perturbation, even a vacuum magnetic field). This modifies the toroidal current profile in a way that is unfavorable for the further growth of tearing modes. A large applied helical field, on the other hand, produces an island so wide that it touches the edge of the plasma so that confinement is lost over a large part of the plasma. Alternatively, at high density or low current, or in a plasma whose temperature is dominated by radiation from impurities, the current channel shrinks so that the primary magnetic islands are in the relatively cold edge of the plasma where tearing modes can grow rapidly, precipitating a disruptive instability. For the same reason, a material obstruction can make the plasma disruptive. Starting with this plausible explanation and qualitative agreement, researchers are trying to develop a more complete theoretical description with quantitative agreement and predictive value.

Even in the absence of disruptive instabilities, fluctuations attributed to more benign instabilities are routinely observed under normal tokamak operating conditions. For more than a decade, researchers have observed rotating helical magnetic structures, called Mirnov oscillations (after S. V. Mirnov of the Kurchatov Institute in

Moscow), which can be easily detected using small coils of wire at the edge of the plasma or beyond. If the toroidal current is raised, the amplitude of these Mirnov oscillations becomes larger and they apparently contribute to a deterioration of the energy confinement in tokamaks long before the toroidal current becomes so large that the Kruskal-Shafranov stability criterion is violated. These helical magnetic structures are generally attributed to relatively benign magnetic islands that evolve gradually during the course of most tokamak discharges. There is evidence of this from detailed experimental observations and there are analytic as well as computational theoretical studies which indicate that the width of magnetic islands should saturate at a few tenths of the plasma radius under the appropriate circumstances, but as yet there has been little quantitative agreement between theory and experimental observation of Mirnov oscillations. Also, simple estimates have been used to demonstrate that islands should rotate through the plasma, mainly because of finite Larmor radius effects (due to the gyroradius of ions and electrons in the magnetic field), but no detailed analysis has succeeded. Comparison between theory and experiment has been hampered by the fact that it is very difficult to make direct measurements of crucial plasma properties, such as the plasma current profile, and the results from theoretical computations seem to depend sensitively on details of the plasma model, such as heat transport and finite Larmor radius effects. In the meantime, Mirnov oscillations by themselves do not appear to be very dangerous and, while they appear to play an important part during a disruptive instability, they do not seem to be a prime cause of disruptions.

The last of the large scale fluctuations normally observed in tokamaks was just discovered in 1974 when S. Von Goeler, W. Stodiek, and N. Sauthoff at Princeton Plasma Physics Laboratory observed a periodic signal on the soft X rays emitted from near the center of the plasma. On oscilloscope traces, this fluctuation signal looks like sawteeth, with a periodic slow rise followed by an abrupt fall in the signal from the central part of the plasma out to a sharp transition radius, beyond which the signal is characterized by a periodic abrupt rise followed by exponential decay. The main part of this signal is the same all the way around the tokamak. Just inside the transition radius, however, a helical (corkscrew) distortion of the central part of the plasma is observed just before each drop in the signal. The X ray signal is a sensitive indicator of mainly the electron temperature, which had hitherto been measured by laser scattering only at brief instants in time. Today, the detection of soft X rays (with 2 to 20 keV energies) by fast solid-state detectors is an excellent and widely used diagnostic. It is even capable of indicating the width of the magnetic islands that seem to be responsible for Mirnov oscillations.

A remarkably complete scenario for sawtooth oscillations has been developed by B. V. Waddell, G. L. Jahns, J. D. Callen, M. Soler, and H. R. Hicks at Oak Ridge National Laboratory (ORNL). In their model, they have used the fact that the electron temperature and the toroidal current tend to concentrate at the center of the plasma due to simple plasma transport processes under most tokamak conditions (unless radiation due to heavy impurities, for example, cools the center of the plasma too much). When the current density concentrates so much that magnetic field lines near the center close upon themselves, a small kinklike instability grows and abruptly spreads out the temperature and current over the central region of the plasma. The instability involves a magnetic field line reconnection which reorganizes the central part of the plasma while leaving the edge of the plasma essentially untouched. The cycle then begins again with the temperature and current density concentrating at the center of the plasma on a slower transport time scale leading to a new helical instability. This model has produced remarkably good quantitative agreement with experimental observations.

It is clear then that the center of most tokamak plasmas is in a periodic state of turmoil, and the edge is laced with magnetic islands or regions with more complicated magnetic structure. Under suitable conditions, all these structures can interact to disrupt the plasma and radically change the profiles. To some extent, these processes can be controlled by adjusting the input power, toroidal current, filling pressure, purity, and other properties of the plasma. In spite of this involved list of phenomena, tokamaks work remarkably well and their performance is being improved every year.

3. HIGH PRESSURE EQUILIBRIA

In early tokamak experiments, the toroidal current was relied upon almost exclusively to heat and confine the plasma. It is now clear, however, that the toroidal current is limited by an impressive array of instabilities. What then are the prospects for increasing the temperature, pressure, and confinement in tokamaks?

There are essentially three ways being developed to confine a high pressure plasma in tokamaks. One way is to heat the plasma rapidly compared to the time scale of resistive diffusion, by neutral beam injection for example, and rely on induced poloidal currents (currents the short way around the torus) to confine the additional pressure. A second method is to adjust the shape of the plasma, by elongating the cross section or decreasing the aspect ratio (making a fatter toroid), for example, in order to increase the maximum toroidal current without allowing field lines to close upon themselves once around the machine for stability. The third method is to broaden the current profile to allow for a greater maximum toroidal current while maintaining stability. Of course, the best prospect for confining higher pressure plasmas in tokamaks will probably be a judicious combination of all three of these methods. For the sake of illustration, let us consider each of these methods separately.

Consider the effect of poloidal currents first. In the presence of a toroidal magnetic field, the plasma will automatically induce poloidal currents as it is being heated and expands. Essentially, the expanding plasma pulls the magnetic field along with it until the difference between the magnetic pressure outside and inside the plasma prevents further expansion . In another way of looking at the same process, poloidal currents are induced which interact with the toroidal magnetic field to produce additional inward force. (Whenever there is a current or component of current flowing perpendicular to a magnetic field, there will be a J x B or Lorentz force perpendicular to both.)

If the toroidal magnetic field is strong enough, as it is in most tokamaks, only a small amount of expansion produces the needed poloidal current and inward magnetic pressure. The current decays on the time scale of resistive diffusion, which gets longer and longer as the plasma gets hotter.

Not only does the plasma pressure exert an outward force in all directions which must be confined by the magnetic pressure and tension, but there is also a component of this force, called the hoop force, that tends to make the toroidal plasma ring expand along the major radius. The origin of this force can be broken down into three parts: from plasma pressure, from diamagnetic poloidal currents, and from that part of the poloidal magnetic field produced by the toroidal plasma current alone (as opposed to externally applied poloidal magnetic fields). In order to visualize the first contribution, consider the plasma pressure against the faces of any thin wedge of the toroidal plasma column. A small component of these opposing vector forces acts to squeeze the wedge outward and therefore exerts a net force on the plasma column outward along the major radius. The second component comes from the fact that both the toroidal magnetic field and the poloidal current are stronger on the inner edge of the toroidal plasma. These produce a net outward force along the major radius if the poloidal current is diamagnetic and a net inward force if the poloidal current is paramagnetic. In order to visualize the third force, note that the poloidal magnetic field due to the plasma current alone has to squeeze through the hole in the torus and then spray out to fill all the space outside the torus. It follows that this part of the poloidal magnetic field is stronger at the inner edge of the torus and exerts a net outward force on the plasma along the major radius.

In order to prevent the plasma from expanding along the major radius, an externally applied vertical magnetic field is used to reinforce the poloidal magnetic field at the outer edge of the torus and to weaken it at the inner edge. In early tokamaks, this was accomplished by surrounding the plasma with a thick copper or aluminum shell and then relying on image currents in the shell to produce the required vertical magnetic field (as the plasma shifts outward, the poloidal magnetic field becomes compressed against the shell until equilibrium is reached). In more recent tokamaks, the shell has been replaced by electrically driven coils, complete with feedback or preprogrammed systems, to center and shape the plasma in the vacuum chamber.

This vertical magnetic field may pose a problem, however, as the plasma pressure is raised. At high pressure, the required vertical field becomes so large that it could cancel the plasma induced poloidal field at the inner edge of the torus. Outside of this stagnation point, field lines run into the wall and therefore do not confine a hot plasma very well. As the plasma pressure is raised, if this argument is valid, the stagnation point would shift toward the center of the plasma, causing the minor radius to shrink and spoiling confinement.

An interesting way around this problem was developed by J. F. Clarke, D. J. Sigmar, R. A. Dory, and Y-K. M. Peng at ORNL. It has already been pointed out that magnetic field lines can be thought of as being frozen into an electrically conducting fluid. This implies that field lines cannot break or reconnect during any continuous motion of the plasma for as long as the plasma can be considered perfectly conducting. Therefore, if the plasma pressure is raised rapidly enough, all the magnetic field lines that were initially completely within the plasma remain completely within the plasma — they cannot break away and intersect with the wall and the stagnation point cannot move into the plasma. The plasma pressure can then be raised arbitrarily high, with the applied vertical magnetic field increased as needed to keep the plasma well centered, and the currents within the plasma will automatically rearrange themselves to keep the plasma confined. This confinement will be maintained until the induced currents decay somewhat as the result of plasma resistivity. If the plasma is sufficiently hot, and consequently the resistivity very low, such a high pressure plasma is expected to be confined for a long time (more than enough time to produce useable amounts of energy by thermonuclear reactions). This confinement concept, called the "flux conserving tokamak," will be tested during the next few years as more and more neutral beam power is injected into tokamaks.

While rapid heating with flux conservation is a promising approach to the confinement of high pressure tokamak plasmas, there are a number of reasons why it would be an advantage to control the shape and profile of the plasma as well. Probably the most important reason has to do with stability, which will be discussed below. Plasma shaping and profile control can also be used to make more efficient use of the toroidal volume available as the central part of the plasma shifts outward along the major radius, relative to the edge of the plasma, leaving a wasted dead space behind at the inner edge of the toroid. With this in mind, let us first consider shaping the plasma by elongating its cross section.

There are essentially two ways to elongate the plasma cross section — either pull at the top and bottom or push on the sides. One pulls at the top and bottom by using external currents above and below the plasma column running in the same direction as the toroidal plasma current. This reduces the poloidal magnetic field and therefore reduces the magnetic pressure and tension between the plasma and the coils. The plasma responds by bulging out until the curvature and corresponding magnetic tension increase sufficiently while the plasma pressure gradient decreases in the direction of the coils until the forces are brought into balance. Alternatively, in order to push on the sides of the plasma, one uses walls of current along the sides of the plasma running in the direction opposite to the toroidal plasma current. Magnetic field strength is then increased between the plasma and these coils, and the plasma is squeezed into an elongated shape. The same basic techniques can be used to shape the plasma in a variety of ways such as making the cross section into a D shape, which seems to be more favorable for stability, or into a "Doublet" shape (where Doublet is the generic name of a series of tokamaks constructed at the General Atomic Company in San Diego, California) in which the midplane is pinched in and the upper and lower regions bulge out.

A disadvantage of the pulling method is that the plasma tends to be subject to a vertical instability in which the plasma column shifts as a whole toward one or more of the coils that pull on it. If the coils are driven with a fixed current, the plasma tends to be swallowed up by the coil. Even if the coil circuit conserves flux, there is a stagnation point between the plasma and the coils so that the buffer of flux surrounding the plasma does not operate well as a stabilizing mechanism. In order to be effective, a passive (flux conserving) circuit element such as a copper shell or coil must be placed close to the plasma (closer than the stagnation point). For highly elongated plasmas, this stagnation point is very close to the plasma and it tends to move around as the plasma current profile changes.

On the other hand, pushing on the sides of the plasma with walls of current generally does not produce a stagnation point anywhere within the region bounded by the coils, and vertical stability seems to be less of a problem. However, the coils must be very close to the plasma and the plasma current profile must be quite broad for elongation to be effective. This was demonstrated computationally by the late K. U. Von Hagenow at the Max-Planck-Institut fur Plasmaphysik in Germany and experimentally by researchers working on the Belt Pinch at the same institute. If the toroidal current concentrates at the center of the plasma, as it does in most tokamaks, then the central part of the plasma will have a nearly circular cross section even though the external currents have elongated the edge of the plasma. Experimentalists working with the Doublet configuration try to avoid this situation by splitting the central current channel into two toroidal current rings, stacked one on top of the other, and then delicately controlling their position so that the rings do not completely separate or completely merge together. Fortunately, the feedback mechanism needed to do this has to operate only on the relatively slow time scale of resistive diffusion. Nevertheless, these coils must be placed close to the plasma to have a significant effect.

Of course, both the pushing and pulling methods can be used together, and the requirements on external coil position and current are less demanding if only a modest elongation or shaping is desired. In fact, the effects of toroidicity and high pressure naturally tend to shape the central part of the plasma into an oblate D shape. The externally applied shaping field, then, can be used mainly to optimize the shape of the outer part of the plasma so that it makes the most efficient use of the volume within the vacuum vessel. There are a number of advantages to using a D-shaped plasma which make it the most likely candidate for the tokamaks being designed at this time. The D shape is a natural shape for the coils that produce the toroidal magnetic field because these coils are then in a state of pure tension in their own fields (that is, the coils would go to a D shape if they were made out of a flexible material). These coils have been made in a circular shape up to now because the circular shape is easier to manufacture. Finally, a moderately elongated D shape appears to be most favorable for stability, as we shall see below.

4. STABILITY OF HIGH PRESSURE TOKAMAKS

One of the most exciting developments in the field of high pressure tokamaks has been the theoretical prediction of a completely new class of large scale instabilities called ballooning modes. A ballooning mode in general is an instability whose amplitude is not uniform along resonant magnetic field lines — the instability bends magnetic field lines because of the very nonuniform nature of the driving force. Under high pressure tokamak conditions, the predicted ballooning modes are expected to form a flutelike deformation of the plasma column which is strongest at the outer edge of the torus and weakest on the inner edge. This instability, which is essentially analogous to a Rayleigh-Taylor instability, is driven by the centrifugal force of the charged plasma particles moving with random thermal velocities along the magnetic field lines that curve around the outer edge of the toroidal plasma. The instability is opposed by the restoring force of magnetic tension as field lines are bent. Hence there is a threshold predicted for the plasma pressure before this kind of deformation becomes unstable.

The first detailed computational study of ballooning modes was carried out by J. P. Freidberg, F. A. Haas, B. M. Marder, W. Grossmann, and J. P. Goedbloed starting in 1973 at Los Alamos Scientific Laboratory. Using a simple model in which all the current is concentrated at the surface of the plasma, they first demonstrated that cylindrical plasmas with an elongated cross section are violently unstable when the pressure is raised above a critical value, regardless of the helical pitch of the magnetic field. The instability appears to blow out the ends of the plasma cross section. The critical value of the pressure depends on how tight the curvature is at the ends of the elongated cross section. An elliptical cross section is bad, because the curvature at the tips of the ellipse becomes very tight at high elongations, while a "race-track" or a Doublet shape, with more gently curved ends, is better. This instability, therefore, has all the essential features of a ballooning mode. It is driven by a high pressure gradient at a place where the magnetic field lines curve sharply toward the plasma interior, and it is not uniform along field lines. The surface current plasma model does not apply to actual tokamaks, but similar results have been found in more applicable theoretical models.

The findings of Freidberg and his associates came as quite a surprise to the advocates of building tokamaks with a highly elongated cross section. Much of the rationale for these devices was based on the idea that kink modes are suppressed when none of the magnetic field lines close upon themselves once around the toroid, so that a stronger toroidal current can be used to confine higher plasma pressure as the cross section is elongated. Freidberg's team predicted that there was something to be gained by making the plasma only mildly elongated, but the critical pressure rapidly decreases as the cross section is made highly elongated. Debate continues on this subject and experimental results are inconclusive, but the main line of tokamak planning is moving in the direction of moderate elongation, less than 2 to 1 in D-shaped tokamaks and 3 to 1 in Doublet configurations.

The situation gets somewhat worse as the cylindrical plasma is bent into a toroid (a torus with arbitrary cross section). Since the magnetic field runs mostly in the toroidal direction, the toroidal curvature dominates under most conditions over the poloidal curvature. The stability criterion for ballooning modes can be estimated by noting that the driving force, which is the product of the pressure gradient around the outer edge of the toroid and the toroidal curvature (the reciprocal of the major radius) must be less than the restoring force due to the bending of field lines, which is proportional to the square of the magnetic field strength divided by the square of the "connection length" — the length of the perturbation along resonant magnetic field lines around the outer edge of the toroid. For a given toroidal magnetic field and major radius, the plasma can be made more stable by reducing the pressure gradient or the connection length around the outer edge of the toroid. Hence, for maximum pressure confinement, the pressure profile should have the smallest gradient possible — gently decreasing to zero pressure at the edge of the plasma. Also, the helical pitch of the magnetic field should be as large as possible without violating the stability condition for kink modes (such as the Kruskal-Shafranov stability criterion).

A number of research teams are studying ballooning modes with computers. Extensive work has been done by teams led by D. B. Nelson, R. A. Dory, and G. Bateman at Oak Ridge National Laboratory, . L. Johnson, J. M. Greene, and R. C. Grimm at the Princeton Plasma Physics Laboratory, D. Dobrott at General Atomic Company, F. Troyon in Lausanne, Switzerland, and J. A. Wesson at Culham Laboratory, England, among others. The optimization done so far with computers has led to a mildly elongated D-shaped cross section with the lowest aspect ratio allowed by engineering considerations. A stable plasma pressure of nearly 10% of the ambient toroidal magnetic field pressure has been predicted when a very broad current profile is used with the edge of the plasma stabilized by a perfectly conducting wall around the plasma. When the edge of the plasma deforms, under these conditions, an image current in the wall (or equivalently, compression of magnetic flux between the plasma and the wall) provides a restoring force. Without the use of an effective flux conserving wall, more peaked current profiles and lower average pressures are required for stability.

There is a striking change in the character and structure of the macroscopic instabilities as the pressure of the plasma is raised. At low pressure, under conditions that correspond to present-day tokamaks, the instabilities are relatively localized. A kink mode localized near the center of the plasma, modified by resistive and finite Larmor radius effects, appears to be responsible for the observed sawtooth oscillations. The resistive form of a kink mode near the edge of the plasma is believed to be responsible for the relatively localized island structures there, to which Mirnov oscillations are attributed. These instabilities are fairly benign as long as they do not grow so large that they interact with each other or with the edge of the plasma and lead to a disruptive instability. As the pressure is raised to the point where ballooning modes set in, however, the resulting predicted instability forms deep convection cells extending from the center to the edge of the plasma. The flow of plasma in these convection cells is generally strongest around the outer edge of the toroid where the pressure gradient is steepest and, consequently, where the resulting convective transport could do the greatest damage. These ballooning modes are expected to have much the same effect as the analogous Rayleigh-Taylor instability which leads to convective mixing of the fluid or, when viscosity is very large, to enhanced transport by a process known as Benard convection.

Most of the predictions of ballooning modes made so far have used a very simple fluid plasma model, without resistivity, viscosity, heat conductivity, or finite Larmor radius effects. The few calculations and estimates that have included one or more of these effects have not yet indicated any substantial change in the onset of the largest-scale ballooning modes. It is difficult, however, to make the models realistic enough to be sure that the predicted results will agree quantitatively with experiments — the best agreement between theory and experiment under present-day low pressure conditions has been achieved with approximations and geometries that are not suitable for studying ballooning modes. Therefore, a large research effort is now being devoted to this problem.

5. TOKAMAK EXPERIMENTAL PROGRAM

By the end of 1976, the ORMAK tokamak at Oak Ridge National Laboratory had demonstrated several of the prerequisites needed to raise the pressure in tokamaks. Neutral beam injectors were shown to be successful in heating both ions and electrons. Experiments were also performed in which the neutral beam heating power was greater than the resistive heating power, with no adverse effects observed. The combined pressure of the beam and that of the ambient background plasma exceeded 1% of the magnetic pressure, just short of the conditions predicted for the onset of ballooning modes in that tokamak, again with no unusual effects observed. With injection heating, a maximum ion temperature close to 2 keV was achieved in ORMAK as well as in the TFR device in Fontenay-aux-Roses, France. Also, ion temperatures exceeding 2 keV have recently been produced in the PLT tokamak at the Princeton Plasma Physics Laboratory, which is now the most powerful tokamak in the world.

The results just quoted for ORMAK were achieved with 340 kW of neutral beam injected power into a moderate sized machine (80 cm major radius, 23 cm minor radius, 10 to 25 kilogauss toroidal magnetic field). The PLT tokamak at Princeton is now being fitted with more than a megawatt of neutral beam injection power into a considerably larger volume (1.5 meter major radius, 50 cm minor radius, more than 35 kG toroidal magnetic field) in order to achieve record temperatures and confinement times under tokamak conditions.

A key experiment now under construction, which is specifically being designed to test high pressure confinement, is the ISX-B tokamak at Oak Ridge, in which a massive amount of neutral beam injection power (1.8 to 3 MW) will be injected into a tokamak not much larger than ORMAK (92 cm major radius, 26 cm minor radius, and up to 18 kG toroidal magnetic field in ISX-B). In this experiment, the plasma cross section can be controlled from circular to elliptically elongated to D-shaped.

The device is designed to be flexible and easy to change (some tokamaks have to be laboriously cut apart and welded together if any internal changes need to be made).

With so much power being injected into the moderate volume of ISX-B, plasma pressures well above 1% of the magnetic pressure are expected. The maximum pressure is expected to exceed the predicted onset of ballooning modes and the range of available plasma pressure should cover the range of pressure that can be stabilized by adjusting the shape and profile of the plasma. The wall stands away from the plasma in the present model of the experiment (ISX-A) now in operation. Given the flexible design of this series of experiments, a closer-fitting wall, additional coils, additional diagnostics could be implemented, should this become necessary. Past experience has indicated that such flexiblity is extremely helpful when approaching a new phenomenon.

A number of large and powerful tokamaks are now planned or under construction in the United States, the Soviet Union, Western Europe, and Japan. The most powerful tokamak currently being constructed is the TFTR (Toroidal Fusion Test Reactor) device to be completed in the early 1980's at Princeton. This device will supplement the hot background plasma with colliding beams of particles to assure an abundance of fusion reactions. In between PLT and TFTR, Princeton is building the Poloidal Divertor Experiment (PDX) which is designed to shape the plasma, to control the edge in a way that inhibits the influx of impurities from the wall (using a divertor), and to control the density and pressure of the plasma. The third large tokamak in the United States will be the Doublet III device nearing completion at the General Atomic Company in San Diego. This experiment is specifically designed to confine a higher pressure plasma by use of the Doublet elongated cross sectional shape, as described earlier in this article.

As an alternative to using high plasma pressure relative to the magnetic pressure, the Alcator series of experiments at the Massachusetts Institute of Technology are designed with exceptionally high toroidal magnetic fields (85 kG has been achieved). The Alcator experiment holds the world record for tokamak density and for the product of density with confinement time (above 10^{13} sec/cm^3). Other major experiments include JET (Joint European Torus), a huge tokamak to be built in Culham, England, a major series of tokamaks at the Kurchatov institute in Moscow (where tokamaks were originally developed under the direction of the late L. A. Artsimovitch), with the currently operating T-10 tokamak corresponding roughly to PLT in size and the reactor-sized tokamak T-20 in the planning stages, and, a rapidly-growing tokamak program in Japan, culminating in the JT-60 device now being planned.

There is no question that fusion can be produced in tokamaks — large numbers of fusion reactions are already detected in currently operating tokamaks. Given the present rate of steady progress, many researchers are optimistic that tokamaks can produce significant amounts of controlled fusion energy; experiments during the next ten years should demonstrate this. Attention is now being turned to the problem of making this energy production efficient, useful, and attractive, compared to other sources of energy. There is no telling how long this will take, but the sooner it can be achieved, the more comfortable and secure our lives will be.

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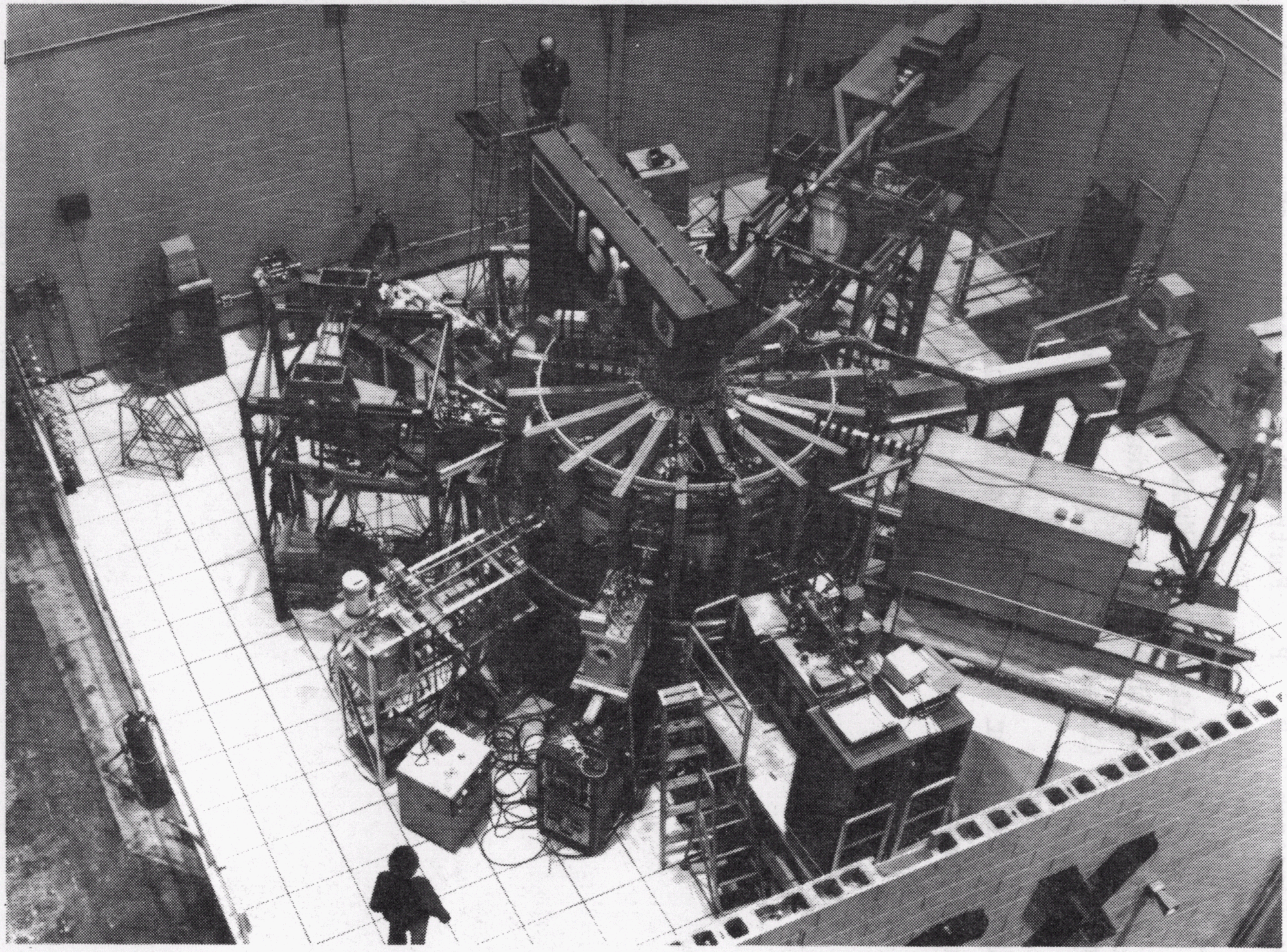

Fig. 1. Photograph of the ISX-A tokamak at Oak Ridge National Laboratory in collaboration with the General Atomic Company. The device is surrounded by diagnostic equipment, including spectroscopes, lasers, microwave guides, and a surface analysis apparatus. This tokamak will soon be converted into the ISX-B experiment in which 1.8 to 3 mW of neutral beam power will be injected in an effort to raise the plasma pressure well above 1% of the magnetic pressure.

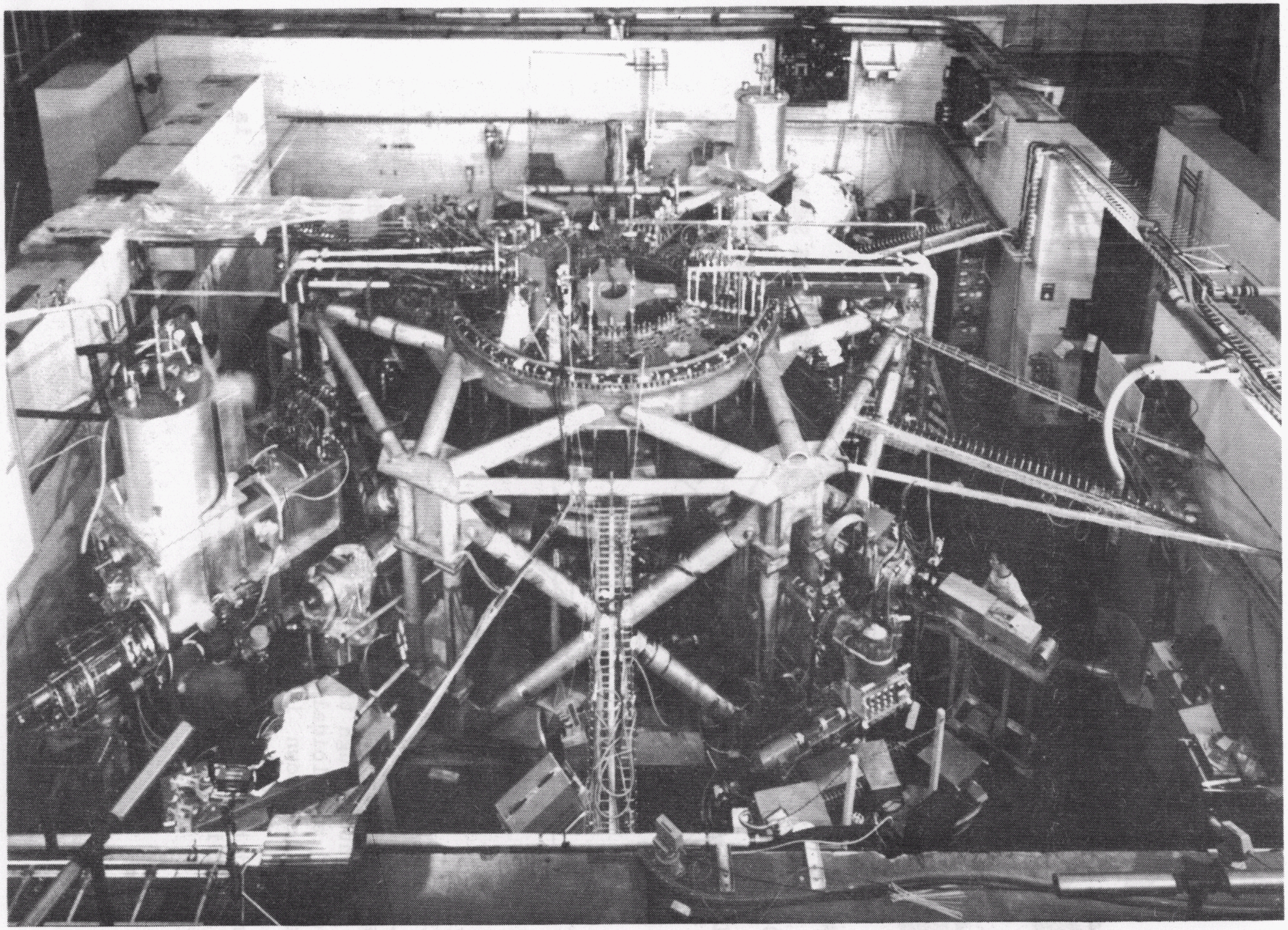

Fig. 2. Photograph of the PLT tokamak at Princeton Plasma Physics Laboratory. The stainless steel box to the lower left is a neutral beam injection line aimed tangential to the toroidal plasma column. Just visible within the tubular supporting structure are the dark blue toroidal field coils and yellow poloidal field coils, which center the plasma and drive the air core transformer. Courtesy of Princeton Plasma Physics Laboratory.

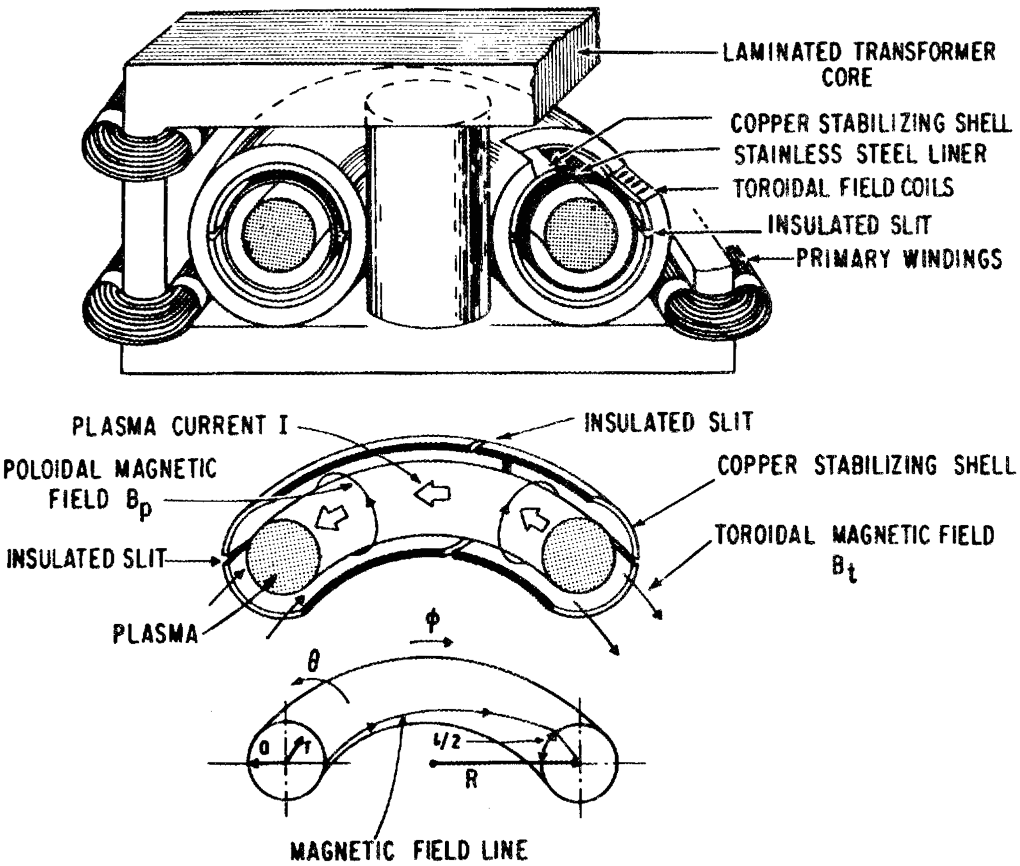

Fig. 3. Schematic illustration showing the operating principles of tokamaks in general. The transformer shown in the top view drives a toroidal current through the plasma, as illustrated in the second view, which produces a poloidal magnetic field which confines the plasma. Additional coils shown in the top view produce the strong toroidal magnetic field needed for large scale stability. A sample magnetic field line, with its slight helical twist around the plasma column, is shown in the third view.

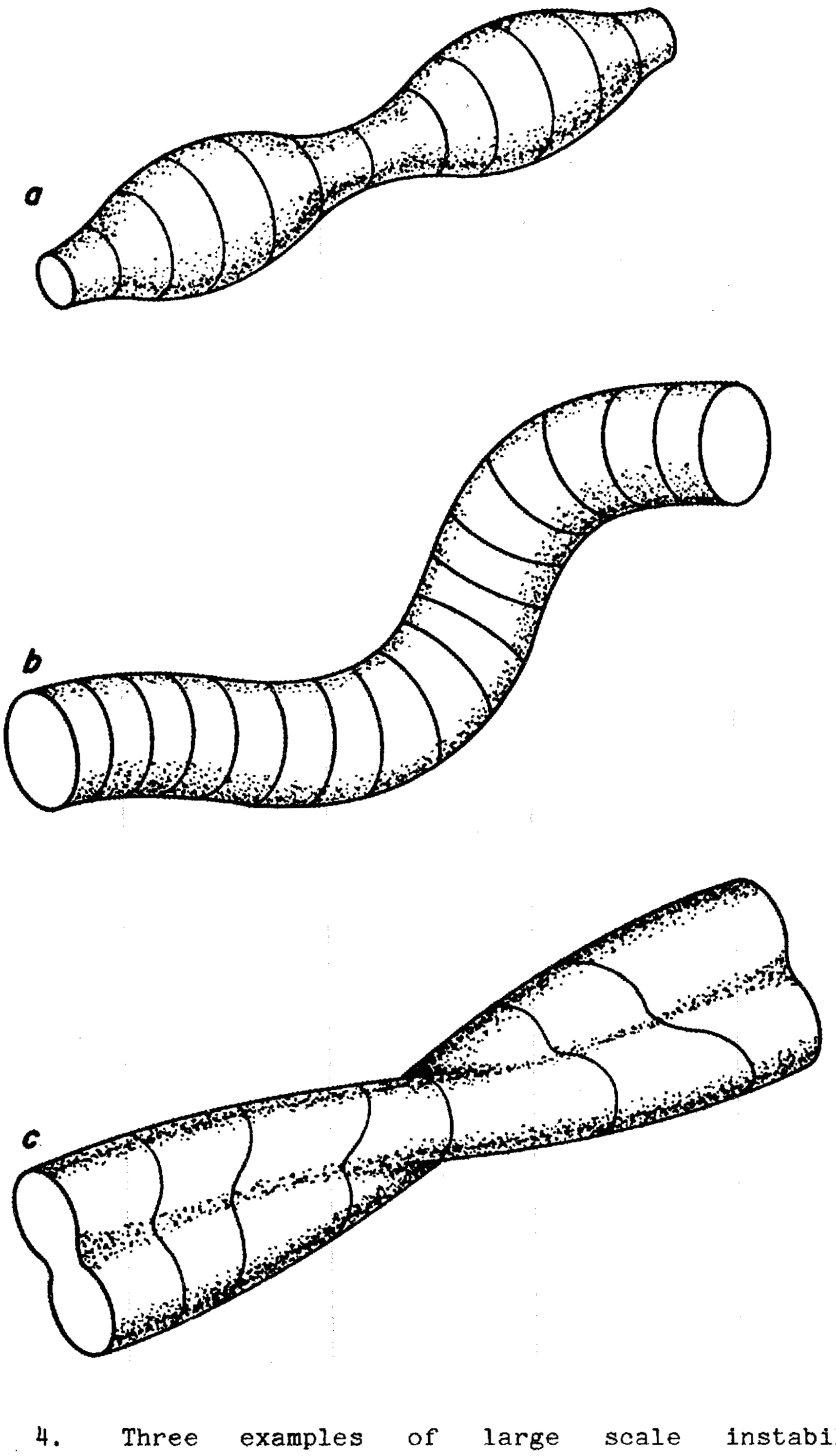

Fig. 4. Three examples of large scale instabilities. Deformations of a straight cylindrical plasma column are shown for a "sausage instability," a kink instability which bends the plasma column into a corkscrew, and a more complicated helical deformation of the plasma column.

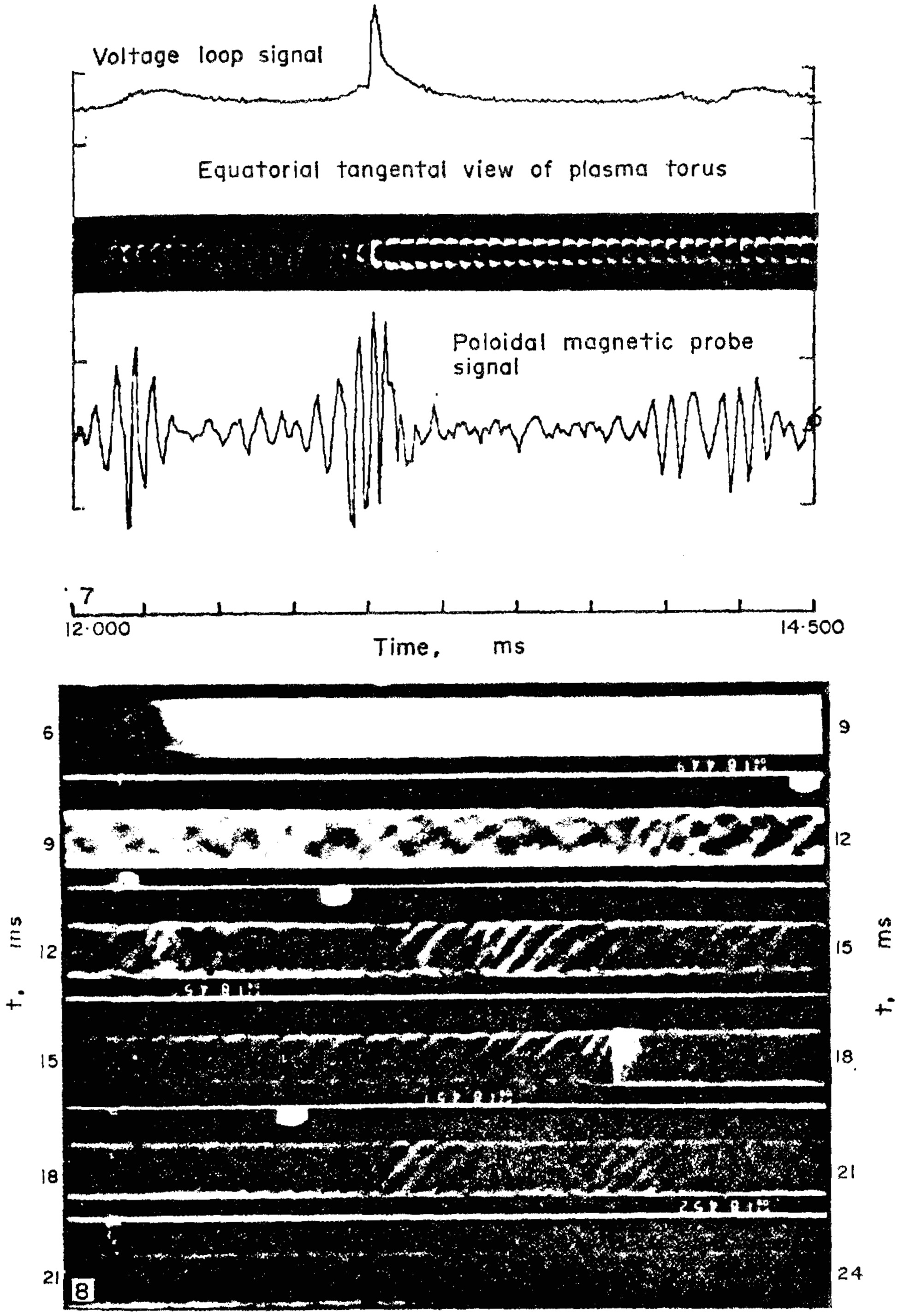

Fig. 5. A photograph of the cross section of the plasma in the ATC tokamak at Princeton, showing helical deformations and a moderately strong disruptive instability. Time proceeds from left to right as the film is rapidly moved past a slit in the wall of the tokamak. Courtesy of R. A. Jacobsen and the Princeton Plasma Physics Laboratory.

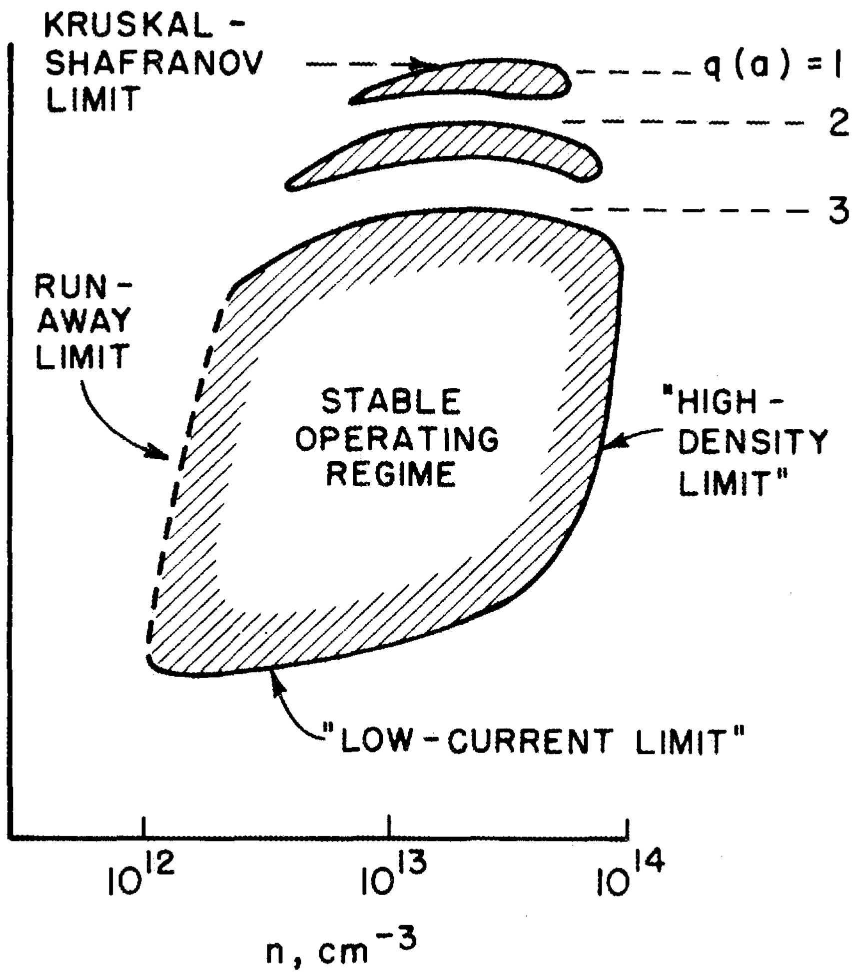

Fig. 6. Rough schematic of the toroidal current (on the vertical axis) as a function of the plasma particle density operating conditions for most tokamaks. Disruptive instabilities terminate the plasma discharge at high current, at high density, and at low current. Highly accelerated electrons absorb most of the plasma energy when low density operation is attempted. The extent of the "stable operating regime" has been broadened in more advanced tokamaks by the use of neutral beam injection, gas puffing, and low impurity conditions. From WASH-1295, courtesy of the U. S. Department of Energy.

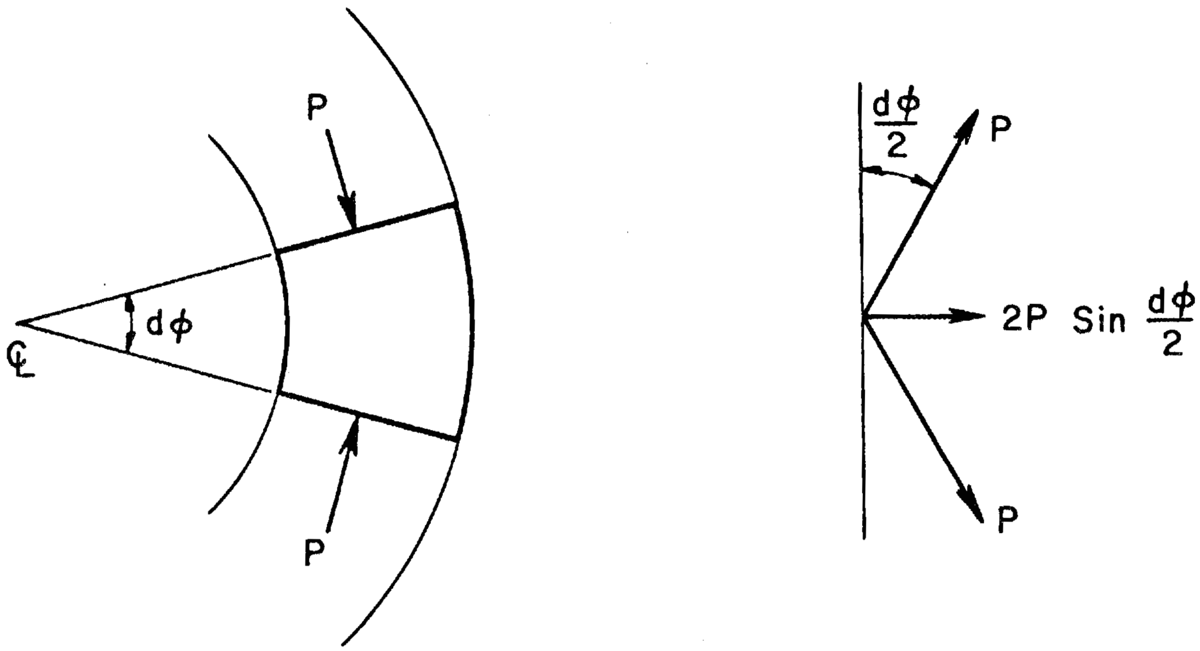

Fig. 7. Illustration showing how the plasma pressure produces an outward force along the major radius of the toroidal plasma column.

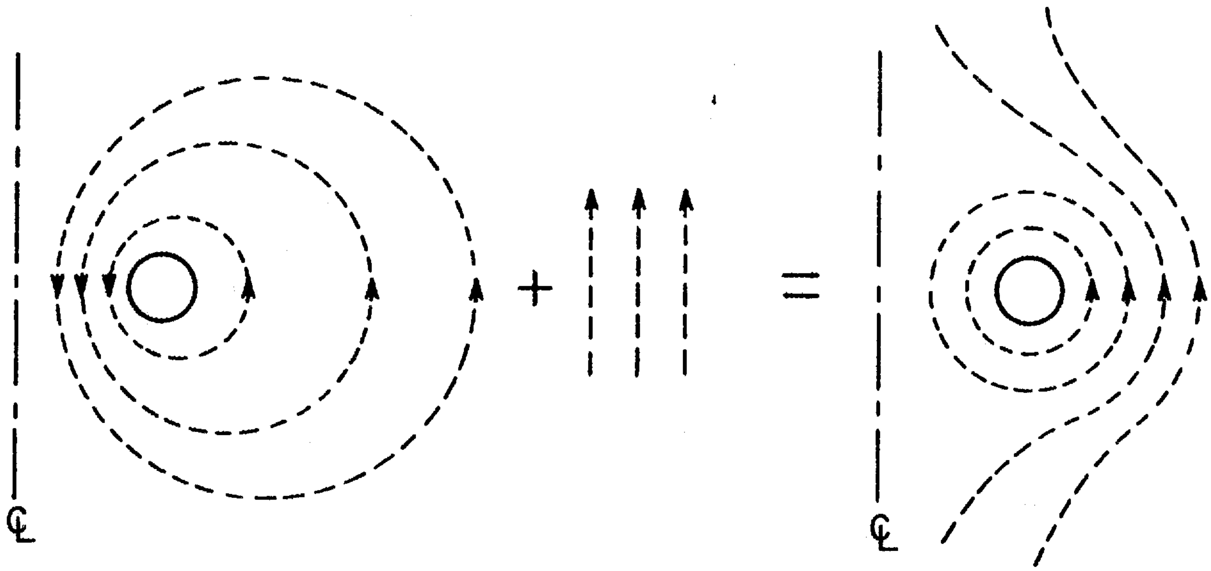

Fig. 8. The part of the poloidal magnetic field due to the plasma current alone contributes to the outward radial force on the plasma column. An applied vertical magnetic field, however, provides a compensating inward radial force.

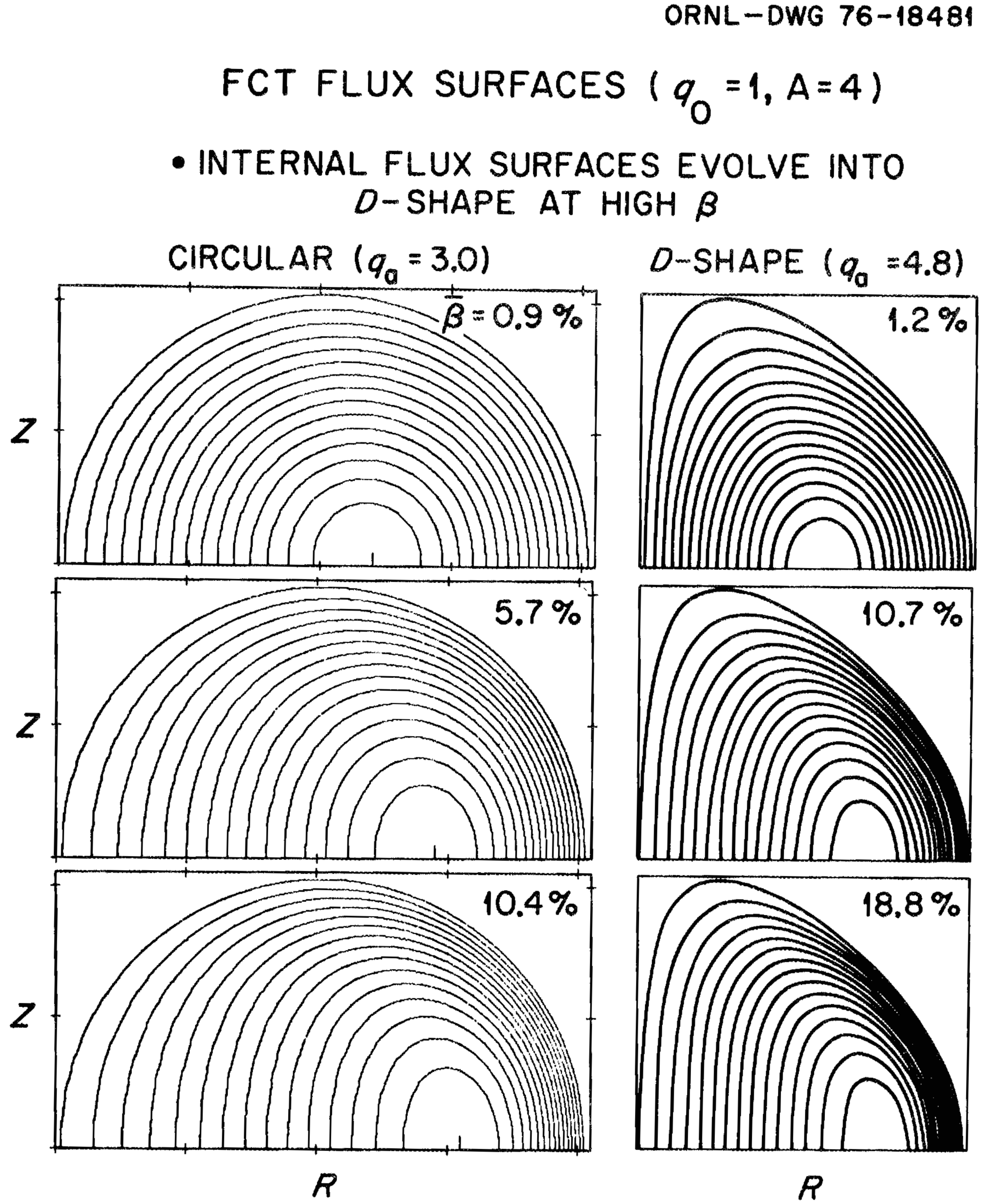

Fig. 9. As the plasma pressure is raised by heating, the contours of constant pressure within the plasma shift outward, as shown in these cross sections of toroidal plasmas. If the plasma is produced with a D shape, as shown in the sequence on the right, there is less shift and the space is used more effectively. Courtesy of R. A. Dory and Y-K. M. Peng, Oak Ridge National Laboratory.

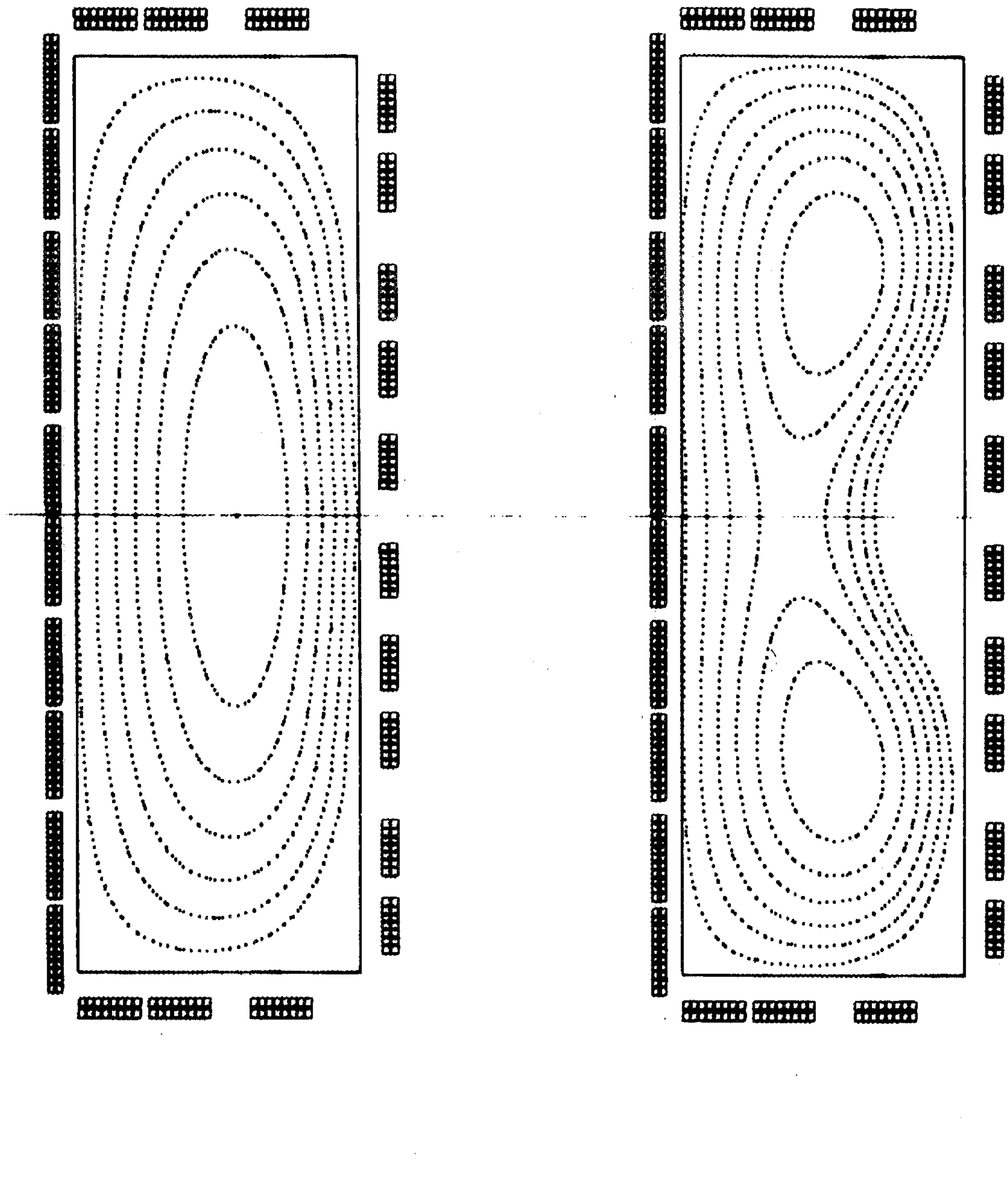

Fig. 10. Cross sections of the contours of constant pressure computed for a toroidal plasma with elliptically elongated cross section and with a Doublet cross section. Courtesy of the General Atomic Corporation and the Electrical Power Research Institute.

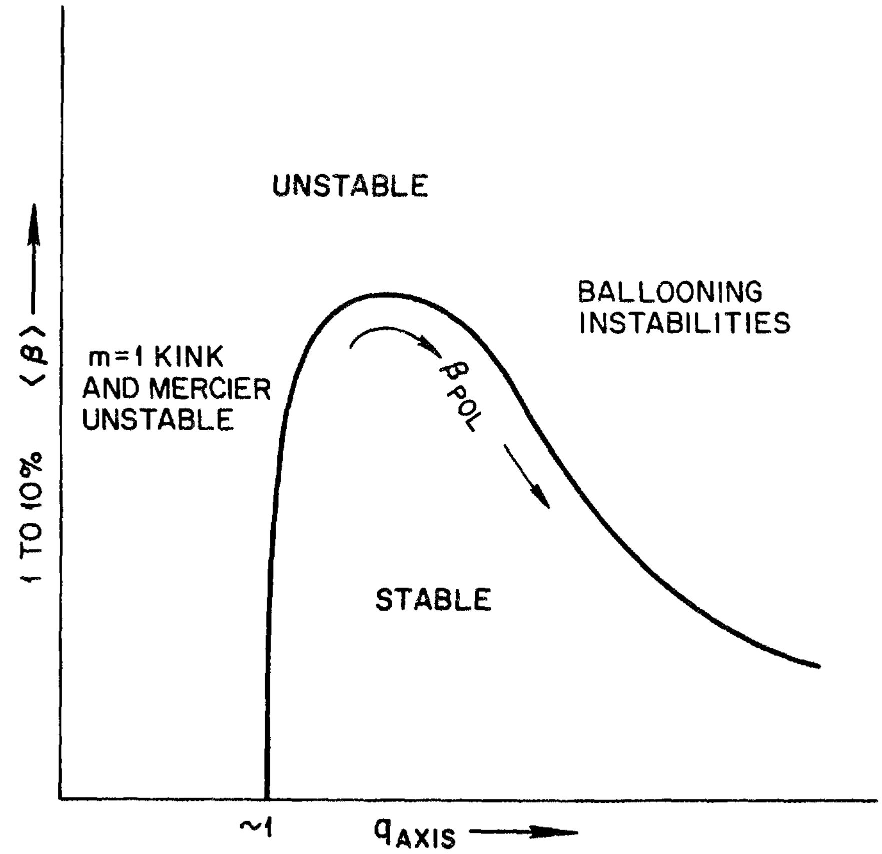

Fig. 11. Stability diagram showing the transition from kink and localized instabilities to large scale ballooning instabilities. Here, beta is the volume averaged plasma pressure divided by the toroidal magnetic pressure, beta-poloidal is the average plasma pressure divided by a measure of the poloidal magnetic field pressure, and q-axis (the minor radius times toroidal magnetic field divided by the major radius times poloidal magnetic field) is inversely proportional to the helical pitch of the magnetic field or, equivalently, inversely proportional to the toroidal current.

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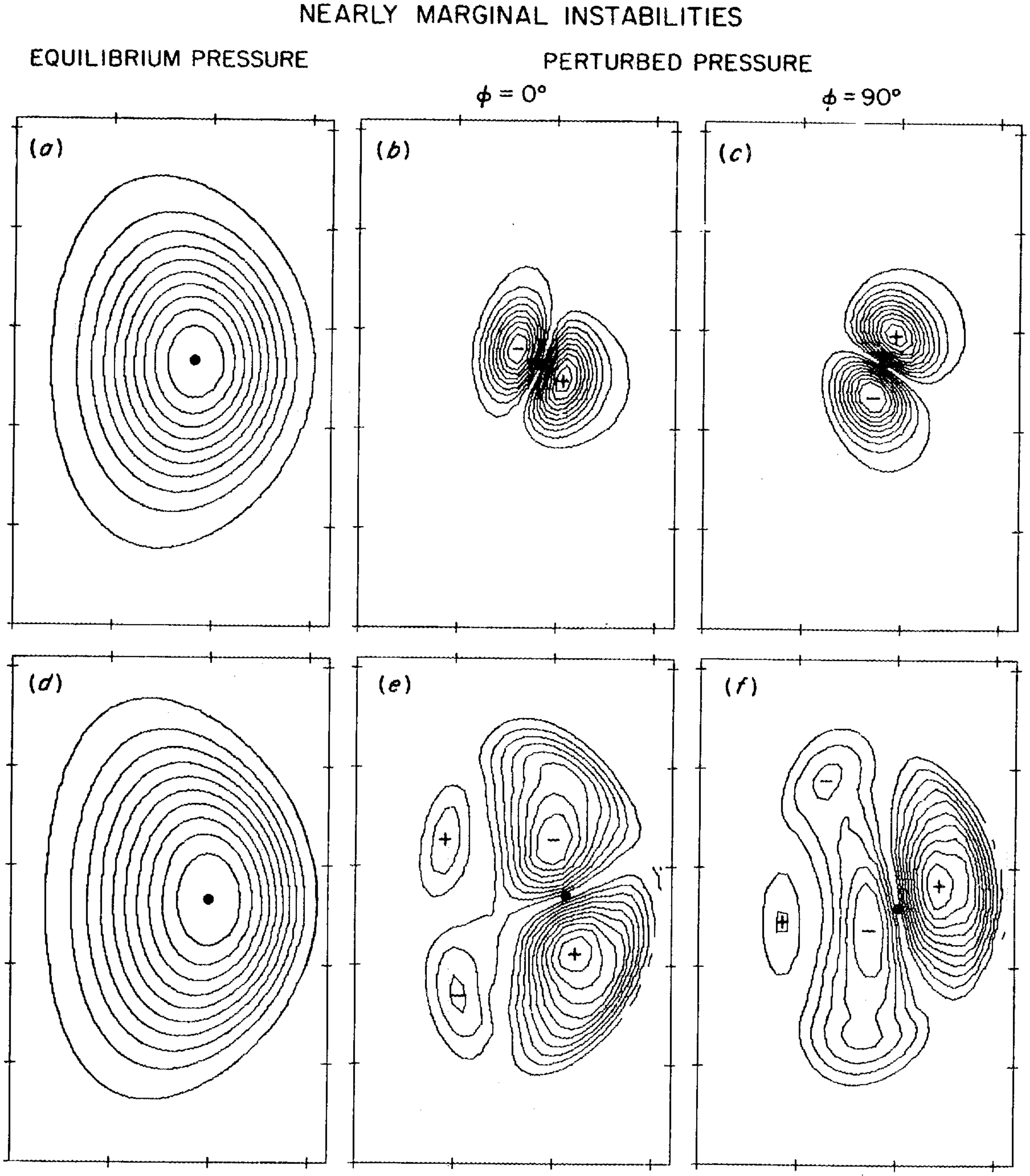

Fig. 12. Perturbed pressure contours for an internal kink instability (top a,b,c) compared to a ballooning mode (bottom d,e,f) which is predicted to occur at sufficiently high pressure. A cross section of the equilibrium pressure contours is shown to the left and two cross sections of the helically twisted perturbed pressure contours are shown to the right. The center line of the toroidal plasma is to the left.

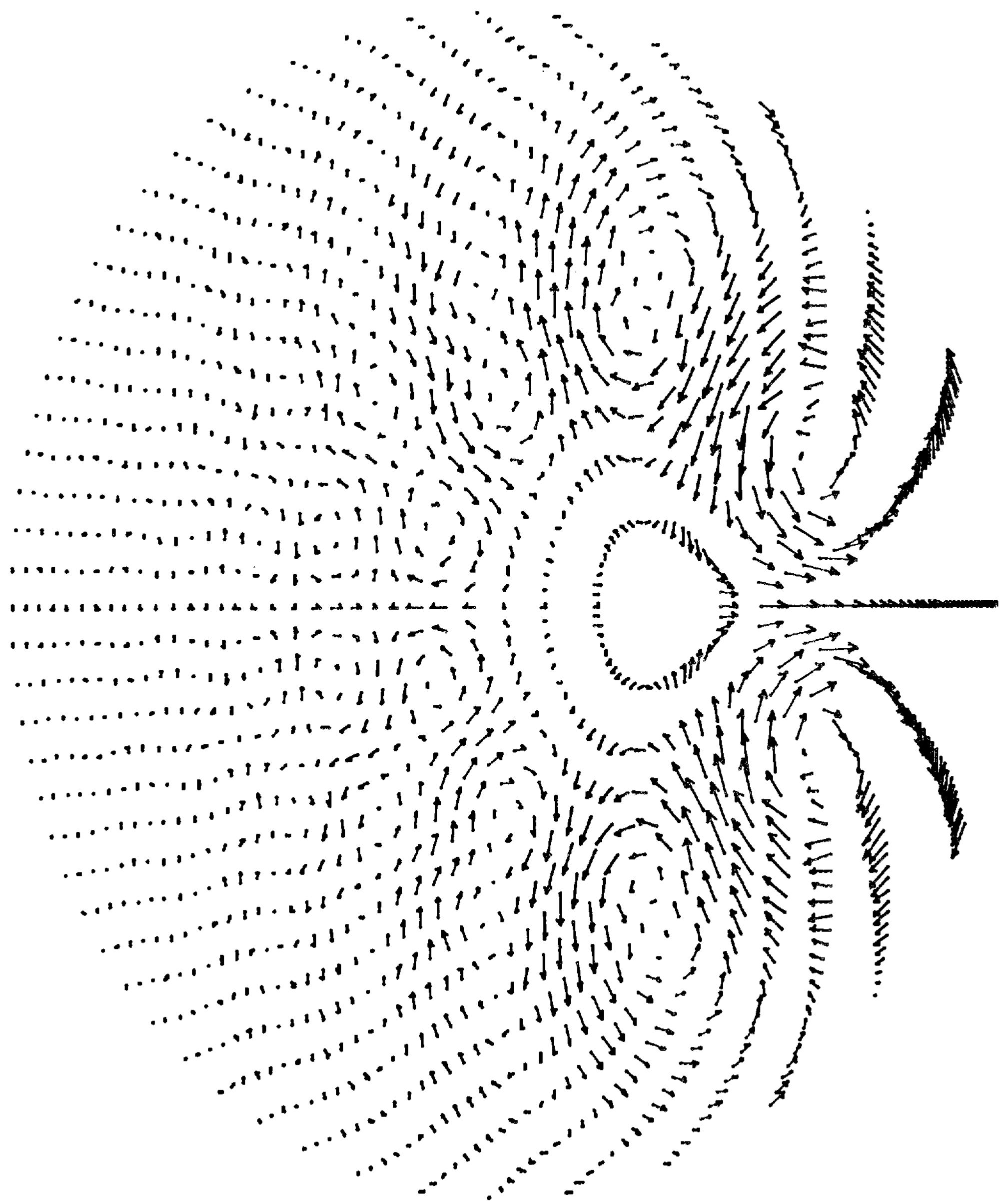

Fig. 13. Velocity flow pattern associated with a large scale ballooning mode in a toroidal plasma with circular cross section (center line to the left). Courtesy of A. M. M. Todd, M. S. Chance, J. M. Greene, R. C. Grimm, J. L. Johnson, and J. Manickam of the Princeton Plasma Physics Laboratory.

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