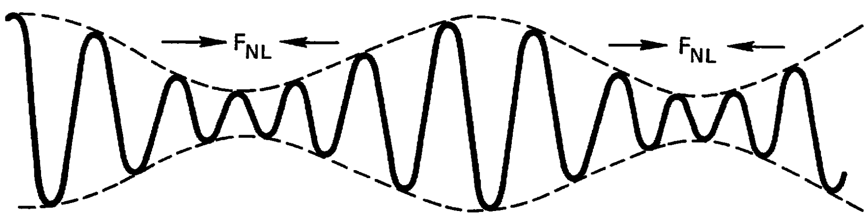


FIGURE 8-24 The ponderomotive force caused by the envelope of a modulated wave can trap particles and cause wave–particle resonances at the group velocity.

(Fig. 8-24), and Landau damping or growth can occur. Damping provides an effective way to heat ions with high-frequency waves, which do not ordinarily interact with ions. If the ion distribution is double-humped, it can excite the electron waves. Such an instability is called a *modulational instability*.

Chapter Nine

INTRODUCTION TO CONTROLLED FUSION

THE PROBLEM OF CONTROLLED FUSION 9.1

It is entirely fitting that this book should end with an introduction, since the study of elementary plasma physics leads to an understanding of the complex problem that originally supplied the impetus for the growth of this new science—the problem of controlled thermonuclear reactions. Since the only fuel required in the ultimate fusion reactor is the heavy hydrogen in seawater, the realization of this goal would mean a virtually limitless source of energy (lasting hundreds of millions of years) at virtually zero fuel cost. The enormous impact this would make on our civilization makes controlled fusion the most important scientific challenge man has ever faced.

Reactions 9.1.1

The first generation of fusion reactors will rely on the following reactions:

$$D + T \rightarrow {}^{4}\mathrm{He}(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV}) \qquad [9\text{-}1]$$

$$n + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He}(2.1\ \mathrm{MeV}) + T(2.7\ \mathrm{MeV}) \qquad [9\text{-}2]$$

Here, n is a neutron and D and T are atoms of deuterium (${}^{2}H$) and tritium (^{3}H), respectively. This reaction, as we shall see, has the lowest ignition temperature and lowest confinement requirement of all. However, most of the energy comes out in the form of a 14-MeV neutron and has to be recovered in a heat cycle, whose thermodynamic efficiency is limited to about 40%. Furthermore, the neutron causes damage to and radioactivity of the reactor walls.

A second disadvantage of reaction [9-1] is that tritium does not occur naturally and has to be bred via reaction [9-2] in a blanket of lithium surrounding the plasma. Fortunately, ^{6}Li is an abundant isotope, comprising 7.5% of natural lithium, of which the earth's crust has a copious supply. There is an inexhaustible supply of deuterium, since 0.015% of the hydrogen in seawater is deuterium, and it is easily separated out.

A reactor fueled with deuterium alone would undergo the following reactions, which occur with about equal probability:

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1\ \mathrm{MeV}) + \mathrm{p}(3\ \mathrm{MeV}) \qquad [9\text{-}3]$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He}(0.8\ \mathrm{MeV}) + \mathrm{n}(2.5\ \mathrm{MeV}) \qquad [9\text{-}4]$$

No tritium breeding is required, and only 34% of the energy appears in the form of neutrons. However, the requirements on the plasma are considerably more difficult to satisfy.

An attractive possibility in a fusion reactor is the use of the charged reaction products to generate electric power directly, thus avoiding the inefficiency of a thermal cycle and minimizing thermal pollution of the environment. If the high ignition temperatures can be achieved, the following reactions, which have only charged-particle products, would be suitable for this purpose:

$$\begin{aligned} \mathrm{D} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + \mathrm{p} + 18.3\ \mathrm{Mev} \\ \mathrm{p} + {}^6\mathrm{Li} &\rightarrow {}^4\mathrm{He} + {}^3\mathrm{He} + 4.0\ \mathrm{Mev} \qquad [9\text{-}5] \\ \mathrm{p} + {}^{11}\mathrm{B} &\rightarrow 3\,{}^4\mathrm{He} + 8.7\ \mathrm{MeV} \end{aligned}$$

9.1.2 The Necessity for Plasma

Since ions are positively charged, the Coulomb force of repulsion has to be overcome before the reactions of Section 9.1.1 can occur. Consequently, the nuclei have to be accelerated to considerable energy in order to penetrate the Coulomb barrier. For instance, the cross section σ for the D–T reaction rises sharply as energy is increased up to 50 keV. A peak in σ is reached near 100 keV, and σ decreases gradually at higher energies. A beam of deuterons from an accelerator cannot be used, for it can be shown that if the beam is directed at a target of solid tritium or deuterium, for instance, most of the energy is lost in ionizing and heating the target and in elastic collisions. Colliding beams cannot be made dense enough to give a fusion energy output larger than the energy required for acceleration. The solution is to form a Maxwellian plasma in which the fast particles in the tail of the distribution undergo fusion. Elastic collisions do not change the distribution function if it is Maxwellian, and the energy used to heat the plasma is retained until the particles react or escape from the chamber. This is the reason for the term *thermo*nuclear reactions.

Ignition Temperature 9.1.3

The power produced per cm^3 in D–T reactions is

$$P_r = n_{\mathrm{D}} n_{\mathrm{T}} \langle \sigma v \rangle W \qquad [9\text{-}6]$$

where $\langle \sigma v \rangle$ is averaged over the Maxwellian distribution, and W is the 17.6 MeV of energy released in each reaction. To maintain the plasma temperature, this power must exceed that which is lost. Even if the plasma were perfectly confined, there is an inescapable energy loss due to radiation by the electrons. This radiation, called *bremsstrahlung*, is emitted when electrons make elastic collisions with the ions and therefore radiate as accelerated charges. The bremsstrahlung power is given by

$$P_b = 5 \times 10^{-31}\, Z^2 n^2 (KT_e)^{1/2}_{\mathrm{keV}} \qquad [9\text{-}7]$$

Both P_r and P_b vary as n^2, but P_r increases much more rapidly with KT than does P_b. An *ignition temperature* can be found by equating P_r to P_b and assuming that the product ions have enough time to transfer their energy to the other ions and to the electrons by Coulomb collisions, so that all the temperatures are equal. For the D–T reaction, the ignition temperature is about 4 keV; for the D–D reaction, it is about 35 keV. For the high-Z reactions of Eq. [9-5], even higher temperatures would be required.

The Lawson Criterion 9.1.4

To produce more energy by fusion than is required to heat the plasma and supply the radiation losses imposes a condition on plasma density n and confinement time τ, as well as on the temperature. It is assumed that the fusion energy, the bremsstrahlung energy, and the kinetic energy of escaping particles (the escape rate is determined by τ) are all recovered thermally with an efficiency not exceeding 33%. It turns out that n and τ occur only in the product $n\tau$. The minimum value of $n\tau$ required is about 10^{14} cm^{-3} sec for D–T and about 10^{16} cm^{-3} sec for D–D. This is called the *Lawson criterion*. It is possible in principle to lower these figures by using complex schemes, such as combining beams with plasmas, or by more efficient energy recovery, such as direct conversion to electricity.

9.1.5 Major Problems

The problems involved in developing a fusion reactor may be divided into three general areas:

1. Plasma confinement
2. Plasma heating
3. Fusion technology

Confinement has to do with satisfying the Lawson criterion on $n\tau$. There are two different approaches: confinement by magnetic fields, with $n \approx 10^{15}$ cm^{-3} and $\tau \approx 0.1$ sec, and inertial confinement, as in laser-produced fusion, in which $n \approx 10^{26}$ cm^{-3} and $\tau \approx 10^{-11}$ sec. Magnetic confinement has received the most attention and is the best understood of the above three areas. Plasma heating is, of course, related to confinement—even a slow heating process would be good enough if the confinement time were very long. The detailed mechanisms in heating are not yet understood. Fusion technology has to do with the engineering design of a reactor apart from the plasma aspects. The real problems in this field have yet to be faced.

In addition, we should add two subcategories on which considerable progress has been made:

1. Plasma diagnostics
2. Plasma purity

To measure the parameters of a plasma and what goes on inside it, a large variety of diagnostic methods have been developed. These involve electromagnetic waves, plasma waves, internal probe electrodes, particle beams, and external sensors. Plasma purity is an experimental problem of considerable importance, since the influx of high-Z atoms from the walls causes rapid loss of energy by atomic radiation. There are devices, called divertors, made to isolate a hot plasma from the walls effectively.

Major Approaches 9.1.6

A large number of ideas for achieving the plasma conditions for fusion have been tried; but although a few nonstandard methods are still being pursued, the main experimental efforts have narrowed down to the following four approaches:

1. Closed systems: toruses
2. Open systems: magnetic mirrors
3. Theta pinch
4. Laser-fusion

In closed systems, the lines of force are confined within the system, even if they do not close upon themselves. Open magnetic systems work on the mirror effect described in Section 2.3.3. Pinches are plasmas carrying sufficient current to generate their own magnetic fields. The current also serves to heat the plasma. The geometry can be either open or closed. Fusion by laser works on inertial rather than magnetic confinement and, if technically feasible, would obviate the problems of magnetic instabilities.

MAGNETIC CONFINEMENT: TORUSES 9.2

Equilibrium 9.2.1

In Section 2.3.2, it was shown that particles drift out of a simple torus in which the lines of force are circular and close upon themselves. This is a consequence of Ampère's law

$$\oint \mathbf{H} \cdot d\mathbf{s} = \int_0^{2\pi} H_\phi r \, d\phi = 4\pi I \qquad [9\text{-}8]$$

which ensures that $|B|$ varies as r^{-1}; and, therefore, the gyrating particles have unequal Larmor radii in opposite halves of their orbits (Fig. 9-1). The result is that ions and electrons drift to the top and bottom of the torus, and a vertical electric field is set up. This field $\mathbf{E}$ then causes ions and electrons to drift together away from the major axis in the direction of $\mathbf{E} \times \mathbf{B}$. To avoid this effect, toroidal systems require a twist in the lines of force, as shown in Fig. 9-2. A line of force at A with the coordinates (ρ,θ) in the cross section at the right of Fig. 9-2 arrives at the left-hand side at the point A'. The angle θ around the minor axis has been changed by an amount $\Delta\theta$. The angle $\Delta\theta$ after the field line has traversed the torus once and returned to the right-

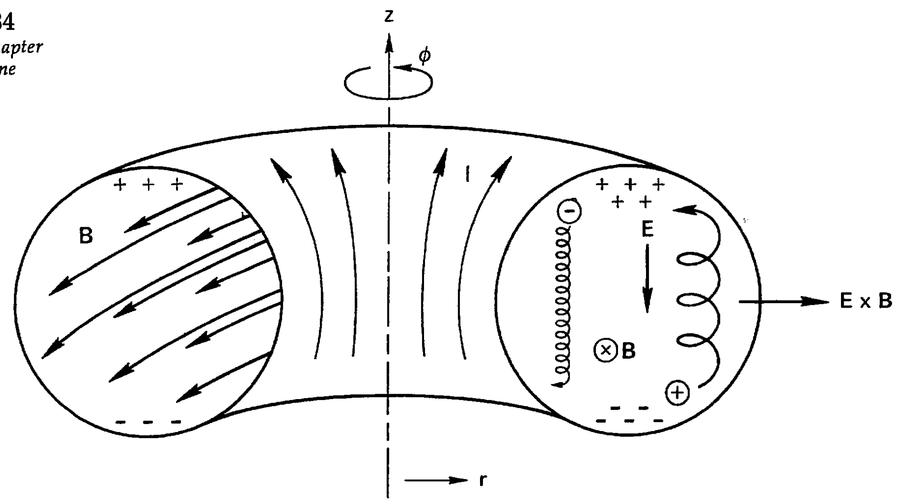


FIGURE 9-1 **In a simple torus in which the lines of force are closed circles, the magnetic field varies as $1/r$. The resulting ∇B drifts cause a vertical charge separation, which in turn causes the plasma to drift outward.**

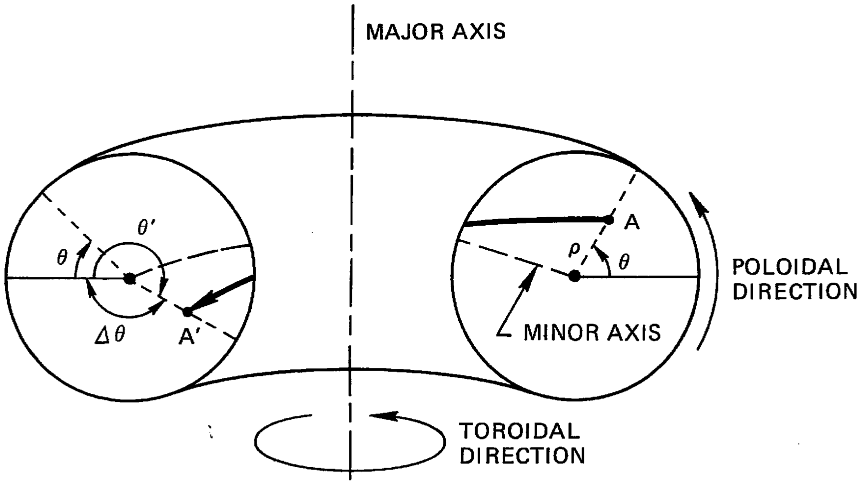


FIGURE 9-2 **In a torus with rotational transform, a line of force A–A' changes its azimuthal angle θ around the minor axis as it winds around the major axis.**

hand side is called the *rotational transform* ι (iota). If there were no collisions, any finite value of ι would prevent the outward drift and give the plasma an equilibrium.

The beneficial effect of the helicity of the lines of force can be seen in two ways. From the single-particle point of view, an ion, say, drifting upward at point A will be moving away from the center of the plasma. Upon arriving at point A', the ion is still drifting upward, but it is now moving toward the center of the plasma. If the thermal motions are much faster than the **E** × **B** drifts, particles will, upon averaging over many cycles around the major axis, stay the same distance ρ from the minor axis if the lines of force do also. From the fluid point of view, one can see that a helical line of force connects regions of positive charge to regions of negative charge (Fig. 9-1), and therefore short-circuits the vertical electric field. If there are collisions, the resistivity is finite; and the rotational transform has to be sufficiently large before an equilibrium is achieved.

Types of Toroidal Systems 9.2.2

Toroidal systems differ in the way the twist in the lines of force is produced. There are four principal ways:

1. External helical conductors: stellarators
2. Internal plasma current: tokamaks
3. Internal conductors: multipoles
4. Internal particle beams: the Astron

Stability 9.2.3

In addition to providing equilibrium, a confining magnetic field must have the proper shape to ensure that the equilibrium is stable. High-frequency electron instabilities are generally not dangerous in toruses, since ions are only slightly jostled by high-frequency fields. The low-frequency instabilities capable of causing the escape of ions are of three classes:

1. Rayleigh–Taylor instabilities
2. Current-driven instabilities
3. Drift instabilities

Because the magnetic field is necessarily curved in a torus, particles feel an effective gravitational field because of the centrifugal force in going around a curve. This gives rise to the "gravitational" instability derived in Section 6.7. If a current is driven through the plasma, either to provide a twist in the magnetic field or to heat the plasma, there are two types of instability possible—one electrostatic and one electromagnetic. The electrostatic type is a two-stream instability (Section 6.6) due to a shift of the centers of the ion and electron distribution functions. The electromagnetic type is called a "kink" instability, which we have not yet discussed.

Figure 9-3 depicts a current flowing in a plasma column along the primary magnetic field $\mathbf{B}_0$. The current produces a poloidal field B_p. If a kink should develop, as shown, the lines of B_p are closer together at the inside of the kink than at the outside. The magnetic pressure $c^2B_p^2/8\pi$ therefore acts to increase the size of the kink; and the plasma is pushed to the walls. Finally, the drift instabilities have the physical mechanism discussed in Section 6-8 and depend on the difference between ion and electron drifts across $\mathbf{B}$, as given by Eqs. [2-59] and [2-66]. A deviation from the Boltzmann relation [3-73] is also required; this can come from finite resistivity, as in Section 6-8, from resonant particles, or from particle trapping in local mirrors (Fig. 5-21).

There are three general ways to prevent instabilities:

1. Magnetic shear
2. Magnetic well (min-$\bar{B}$)
3. Dynamic stabilization

Stellarators and tokamaks depend primarily on magnetic shear, meaning that the pitch angle of the helical lines of force changes with minor radius ρ. Figure 9-4 shows an extreme case of this, in which the field is purely toroidal on the axis and purely poloidal on the outside (for explanation of this terminology, see Fig. 9-2). Shear is effective against instabilities which like to have small $k_\parallel$, as is the case with the gravitational, kink, and drift instabilities. A perturbation aligned with the magnetic field at one radius will encounter field lines at an angle as it grows to another radius in a sheared field.

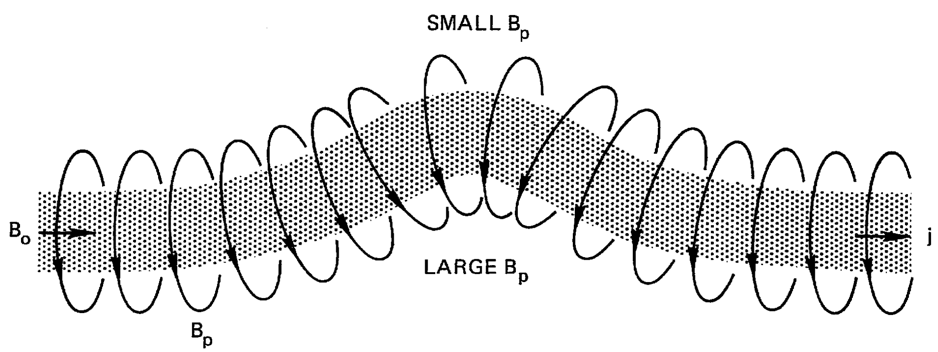
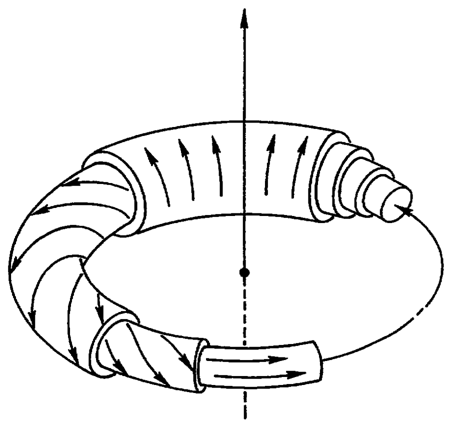


FIGURE 9-3 **Physical mechanism of the kink instability.**



A sheared magnetic field in a torus. FIGURE 9-4

An *average magnetic well*, or *minimum-average-B*, system has field lines which curve more toward the center of the plasma than away from it. Such fields are easier to produce with currents internal to the plasma and are described more fully in the section on multipoles. Internal ring and internal beam devices rely primarily on min-$\bar{B}$ stabilization.

Dynamic stabilization by oscillating **E** or **B** fields can also prevent instabilities by applying a time-varying shear in **E** or **B**. A more efficient method is *feedback stabilization*, in which the phase of an unstable wave is detected, and a force is applied to the plasma (e.g., by an external coil) in the proper phase to suppress the instability.

Stellarators 9.2.4

A stellarator is a toroidal system in which the rotational transform and shear are entirely produced by external windings. The field lines do not close upon themselves but stay more or less at the same minor radius as they go around the torus. The field lines form nested magnetic surfaces, as shown in Fig. 6-3. If a field line is followed long enough, it will cover a magnetic surface but will not leave it; hence, a particle following a field line will be confined. A typical stellarator magnetic surface has a triangular cross section, as shown in Fig. 9-5. The theory of equilibrium and stability in such a geometry is quite complex, but calculations can be simplified greatly by an *energy principle*. In this method, stable and unstable perturbations can be distinguished by whether they increase or decrease the energy of the plasma–magnetic field system.

Even classical diffusion is not simple in such a geometry. The necessity for current along **B** to short-circuit the charge separation of Fig. 9-1 gives rise to additional friction with the ions. The resultant increase in the classical diffusion rate is called the *Pfirsch–Schlüter* effect. At higher temperatures, the trapping of particles in banana orbits (Fig. 5-21) is expected to occur, and the neoclassical diffusion law (Fig. 5-22) would obtain. Although it is possible to see this effect in some experiments, in most cases the observed diffusion follows the Bohm law (Fig. 5-20). Reasons for the failure of stellarators to confine plasma as well as they should may be as follows: (1) There is insufficient shear to stabilize all instabilities; (2) since the system is not totally symmetric about the major axis, asymmetric electric fields may arise which cause a convection of plasma from one magnetic surface to another; (3) small magnetic errors can cause lines of force to wander between magnetic surfaces.

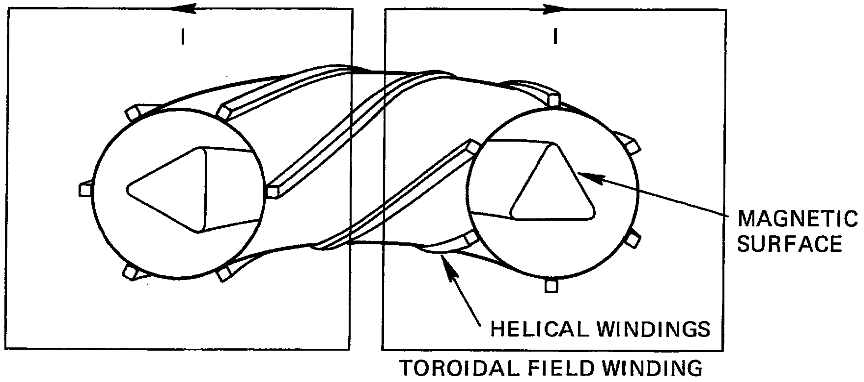


FIGURE 9-5 **In a stellarator, shear and rotational transform are provided by conductors wound helically around the plasma. This is an $l = 3$ system, in which three pairs of wires cause a triangular deformation of the magnetic surfaces.**

Tokamaks 9.2.5

Promoted by L. A. Artzimovich in the U.S.S.R., a tokamak has a strong toroidal magnetic field supplemented by a poloidal component produced by a large current in the plasma itself. Being perfectly symmetric about the major axis, a tokamak is both simpler to analyze and simpler to construct than a stellarator. However, since the plasma is heated by the Joule dissipation of the current itself, and since the current is needed to produce the rotational transform for equilibrium, the problems of confinement and of heating cannot be examined separately. Furthermore, since the plasma current must be induced by a transformer, a tokamak cannot operate in steady state, as can a stellarator; the plasma is created and destroyed in each pulse of the transformer. In spite of these shortcomings, the tokamak has been the most successful of the toroidal devices.

Figure 9-6 shows the main components of a tokamak. In addition to the usual toroidal field B_t and the plasma-produced poloidal field B_p, a third field B_v in the vertical direction is needed to counteract the natural tendency for a current ring to expand. That is, the poloidal magnetic pressure $B_p^2/8\pi$, being larger on the inside, tends to increase the major radius of the plasma. The field B_v is directed so that the $\mathbf{j} \times \mathbf{B}_v$ force is radially inward. This field can be produced by external coils or by the image current in a highly conductive copper shell.

For the rotational transform ι to work, it must not be an integral multiple of 2π. Otherwise, the field lines would close upon themselves, would not cover the whole magnetic surface, and would not enable electrons to go wherever necessary to cancel space charge. For reasons of stability, ι cannot exceed 2π, even if it is not an integral multiple thereof. Consequently, the current cannot be increased indefinitely in an attempt to reach higher temperatures. Let us compare two tokamaks with different *aspect ratios* R/a, where R and a are the major and minor radii. The rate at which a line of force at the plasma surface winds around the major axis is proportional to B_t/R, and the rate at which it winds around the minor axis is proportional to B_p/a (cf. Fig. 9-2). The

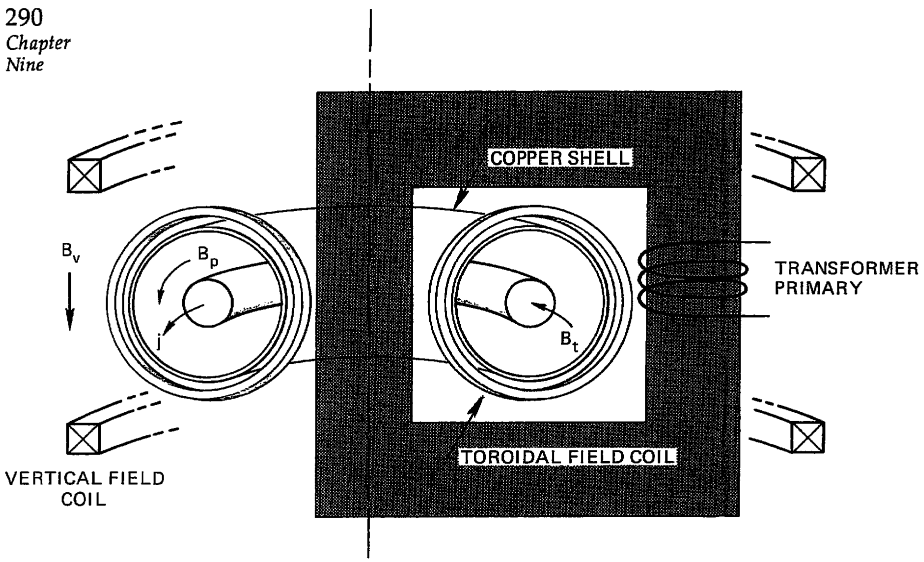


FIGURE 9-6 In a tokamak, the toroidal field component B_t is produced by the ordinary type of coils, while the poloidal component B_p is produced by a large plasma current induced by a transformer. Additional stabilizing forces are provided by a weak vertical field B_v and by eddy currents in a highly conducting copper shell.

rotational transform is therefore proportional to B_pR/B_ta. The quality factor

$$q \equiv \frac{B_t}{B_p}\frac{a}{R} = \frac{2\pi}{\iota} \qquad [9\text{-}9]$$

indicates how far a tokamak is from the stability limit at $\iota = 2\pi$, or $q = 1$, which is called the *Kruskal–Shafranov limit.* For *heating,* however, one wishes to increase j, which is proportional to B_p/a, so that the lowest value of q consistent with stability is desirable. In practice, stable operation with $q < 2$ or 3 is not easily achieved. All else being equal, short, fat tokamaks are better than long, thin ones; small aspect ratios are desirable.

It is possible to improve a tokamak by making the cross section noncircular. After all, the difficulty in toroidal systems stems from the difference in B_t at the inside and outside of the doughnut. One can make Δr small and keep the same total cross-sectional area for the current to flow through by expanding the machine in the vertical direction (Fig. 9-7). There is, of course, a limit to how small Δr can be made, because of the sharp curvature at the top and bottom of the plasma. A further improvement, also shown in Fig. 9-7, is to make the cross section triangular, so that there is more plasma volume at the inner radius than at the outer. At the inner radius, the magnetic field is both stronger and of the right curvature to be stable against the gravitational mode (cf. Eq. [6-55]).

In a stellarator, plasma confinement can be measured by turning off the heating current and watching the density decay in the afterglow. This cannot be done in a tokamak, where the current is needed to shape the magnetic field. Since the current continuously reionizes ions that have gone to the walls, recombined, and reentered the plasma, the density decay is meaningless. What matters is the confinement time of the plasma energy. Just as the particle diffusion rate does, the energy diffusion rate also is expected to follow the neoclassical diffusion law (Fig. 5-22) imposed by toroidal effects. The ions indeed are found to follow this law much better than the Bohm law (Eq. [5-111]), indicating that the amplitude of instabilities is not large. There is, however, an anomalous transport of electron energy and an anomalously fast penetration time for the current induced in the skin of the plasma by the

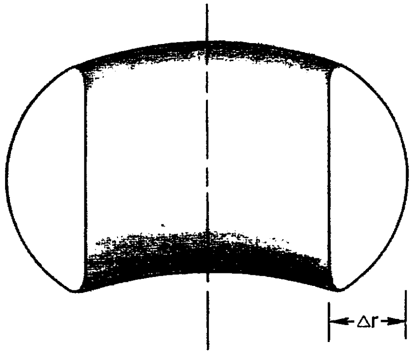


FIGURE 9-7 Tokamaks with a noncircular cross section like this are theoretically superior to circular ones.

heating transformer. Temperatures of the order of 1 keV and densities above 5×10^{13} cm^{-3} have been achieved, but the value of $n\tau$ is still about two orders of magnitude below the Lawson criterion. The value of τ can presumably be increased simply by increasing the size of the tokamak, but there remains another problem. Ohmic heating falls in efficiency as KT_e is increased, and an auxiliary heating method must be found to reach thermonuclear temperatures.

Figure 9-8 is a photograph of a typical tokamak, the ST tokamak at the Princeton Plasma Physics Laboratory. Figure 9-9 is a drawing of the ATC tokamak at Princeton. This machine was used to test adiabatic compression as a means of auxiliary heating.

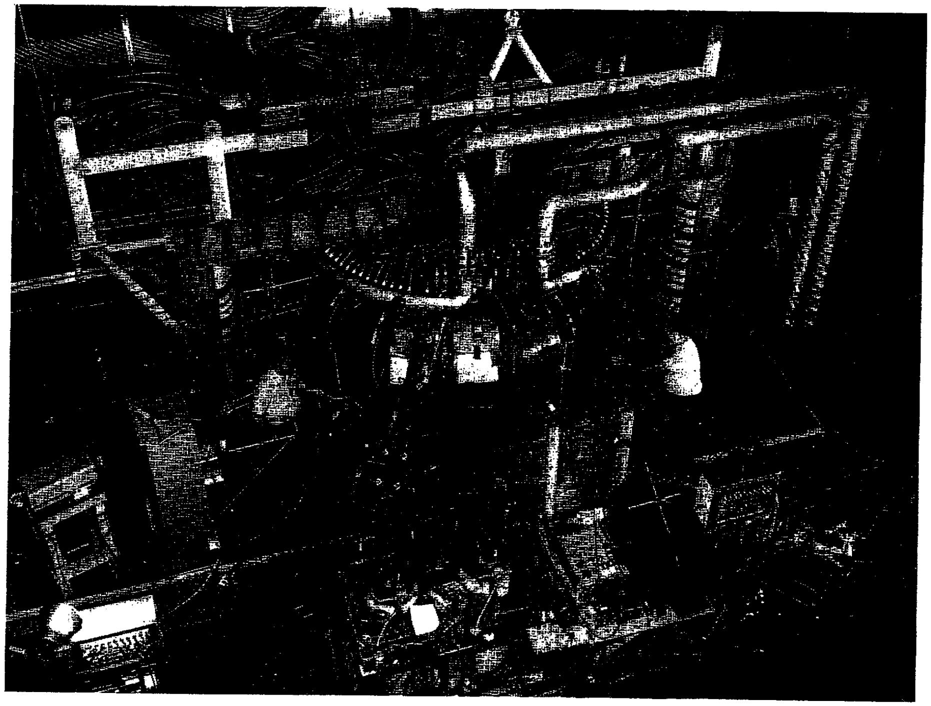
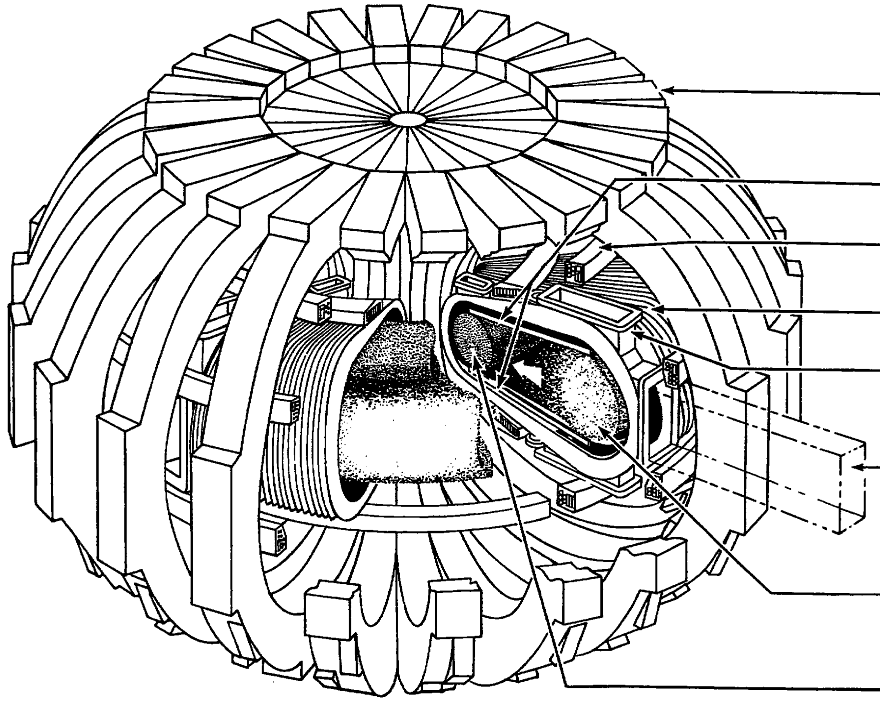


FIGURE 9-8 **The ST Tokamak at the Plasma Physics Laboratory at Princeton, New Jersey.** [Sponsored by the U.S. Atomic Energy Commission.]



Adiabatic Toroidal Compresser (ATC)

1. Toroidal Field Coils (24)
2. Rail Limiters
3. Poloidal Field Coils
4. Corrugated Stainless Steel Vacuum Chamber
5. Port Cross (One of 6)
6. To Pumps (6)
7. Initial Ohmic-Heated Plasma
8. Compressed Plasma

FIGURE 9-9 **In the Princeton ATC Tokamak, the plasma is adiabatically compressed (in both major and minor radii) to achieve a higher temperature than ohmic heating can provide.** [Princeton University Plasma Physics Laboratory, sponsored by the U.S. Atomic Energy Commission.]

9.2.6 Multipoles

In contrast to stellarators and tokamaks, multipoles have their magnetic field entirely or primarily in the poloidal direction. Equilibrium and stability are achieved by placing current-carrying conductors inside the plasma so as to form an average magnetic well. This is illustrated by Fig. 9-10, which shows the field lines of the octopole machine at the General Atomic Corporation in La Jolla, California. The copper rings carry current in the same direction, so that there is a stagnation point, or point of zero B, on the minor axis. Plasma trapped in that region sees an increasing magnetic pressure $B_G^2/8\pi$ in every direction. Plasma moving along the outer field lines feels an alternating inward and outward centrifugal force. In the minimum-average-B region not too far from the conductors, the average curvature is favorable; that is, the average centrifugal force is inward, so that the gravitational instability does not occur. This is a very effective stabilization scheme for other instabilities as well. If the **B** field is purely poloidal and the lines of force are closed upon themselves, electrons are unable to short-circuit any electric potentials that might arise between adjacent lines of force. To prevent this, a toroidal field can be applied by passing a current along the major axis. The octopole then has shear as well. Figure 9-11 shows the interior of a large octopole device at La Jolla.

The min-$\bar{B}$ principle can also be implemented with two rings (a *quadrupole*) or with a single ring (a *spherator* or *off-center levitron*). In the latter case, it is necessary to have toroidal and vertical fields as well.

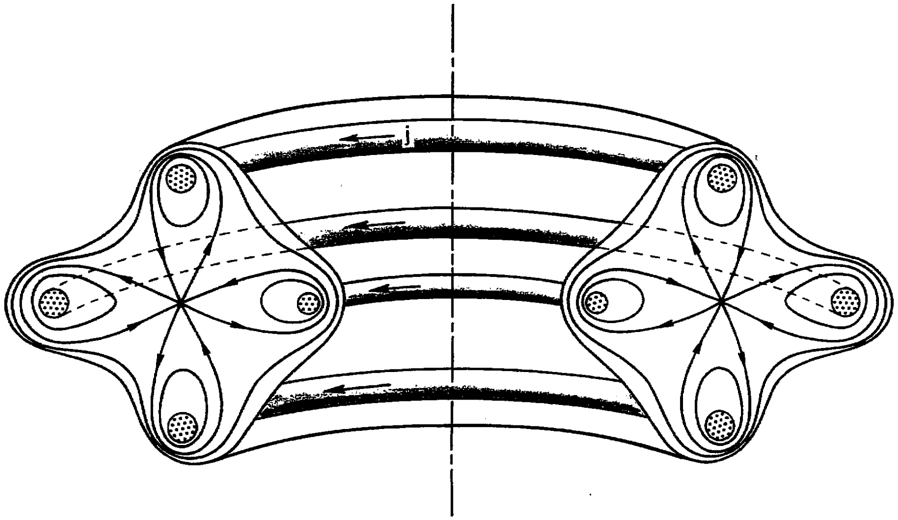


FIGURE 9-10 **In a toroidal octopole, four conducting rings carrying current in the same direction produce a poloidal magnetic field of the shape shown. The plasma fills the center region, where the field is nearly zero, and flows around the rings. On magnetic surfaces further out than the outermost one shown, the plasma does not have minimum-average-B stability and will be lost by gravitational instabilities.**

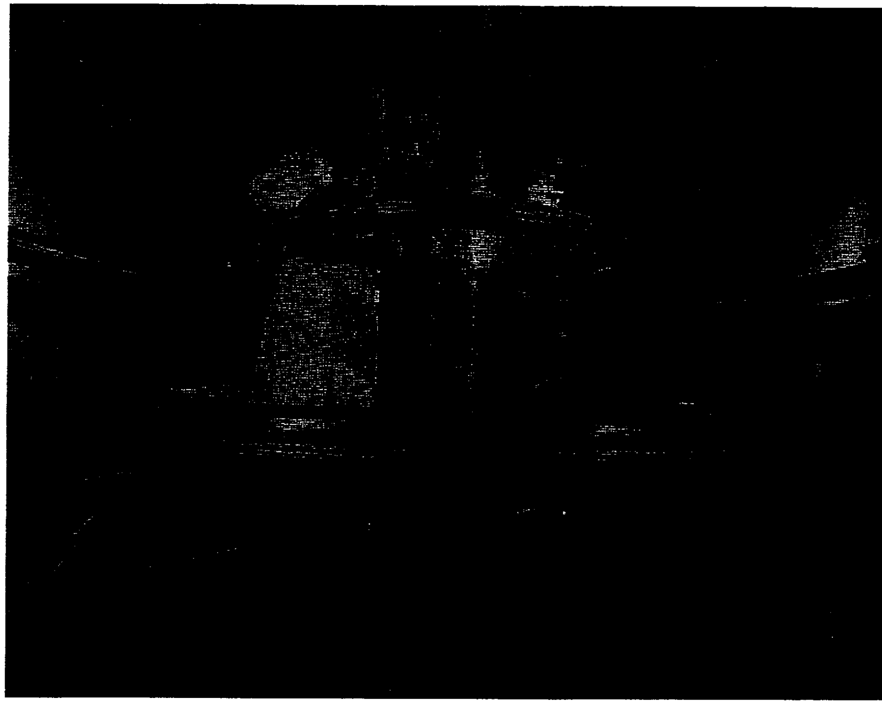


FIGURE 9-11 **The interior of the large octopole device at General Atomic in La Jolla, California. The four conducting rings are supported by small wires passing through the plasma.** [Courtesy of T. Ohkawa, General Atomic Company.]

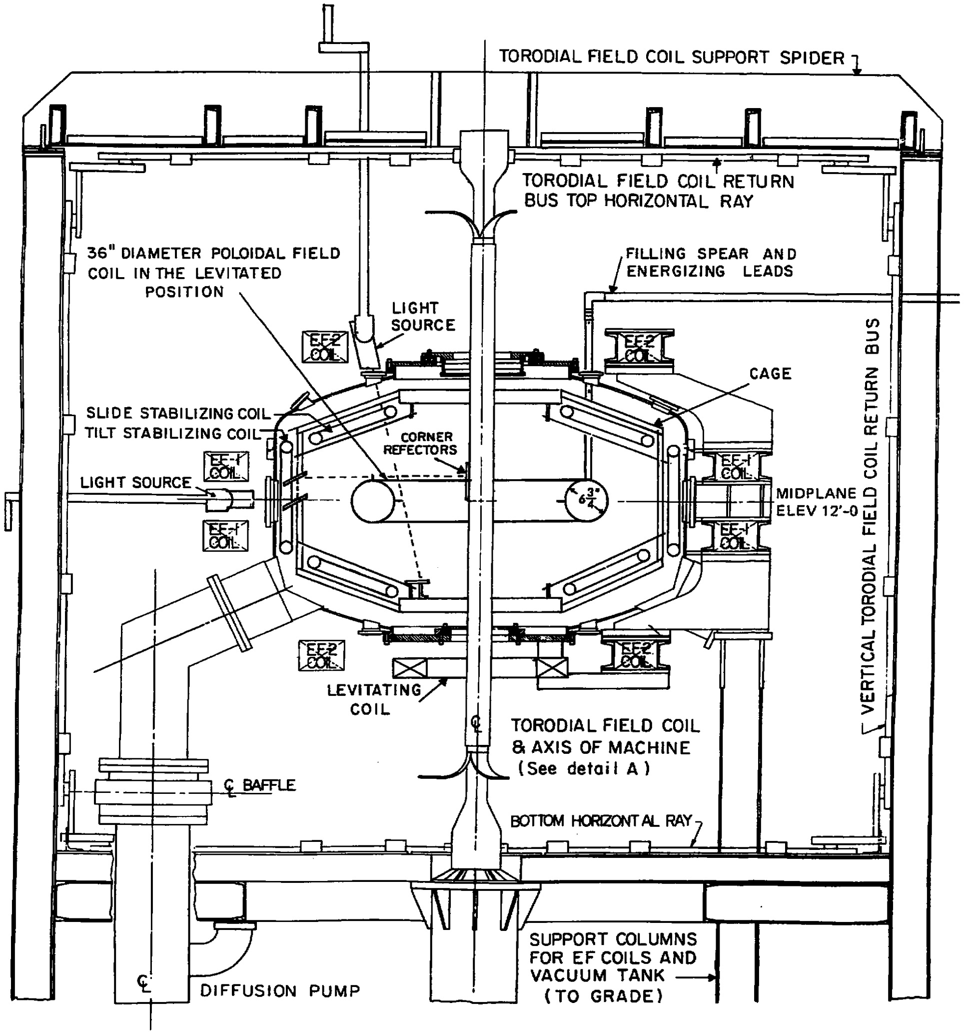


FIGURE 9-12 **Diagram of the FM-1 Spherator at Princeton. The toroidal field is produced by the vertical conductor at the center; the current is returned from top to bottom by a bird-cage array of conductors at the periphery of the device. The poloidal field is produced by a current in a superconducting ring levitated without supports by the magnetic field of the coil at the bottom. Stabilizing coils connected to a feedback system keep the ring from moving. Liquid helium inside the jacket of the ring keeps it at superconducting temperature for as long as two hours before the helium evaporates. The magnetic surfaces are shaped into a minimum-average-B configuration by the additional coils marked EF. The plasma surrounds the ring and has the shape of a tube bent into a circle.** [Princeton University Plasma Physics Laboratory, sponsored by the U.S. Atomic Energy Commission.]

To support and feed current to the internal rings is, of course, a major problem with multipoles. The supports must pass through the plasma, and plasma is lost on them. The only way to avoid this loss is to levitate the rings. This can be done transiently by inducing a current in the rings and using an externally produced magnetic field to lift the rings by the $\mathbf{j} \times \mathbf{B}$ force. The rings fall as the current decays resistively. By cooling the rings to cryogenic temperatures and using superconductors, the current can be maintained almost indefinitely. A multipole can then operate in steady state with levitated rings. Figure 9-12 shows a diagram of the FM-1 spherator at Princeton in which this was done. The operation time was limited to about 2 hr by the need to replenish the liquid He used inside the ring to cool it to 4°K.

Although multipoles are too intricate to be considered seriously for reactor purposes, they have had an important role in toroidal research. The relative merits of shear and min-$\bar{B}$ stabilization have been tested. By eliminating unstable oscillations, multipoles have shown the deleterious effect of magnetic errors and asymmetric electric fields on confinement. The study of multipoles led to the theoretical discovery of a class of *trapped-particle instabilities,* which depend on the inability of particles to circumnavigate a line of force because of the local magnetic mirrors they encounter. Finally, multipoles provided the first experimental verification of the neoclassical diffusion law.

Relativistic Beam Devices 9.2.7

The difficulty of levitating a superconducting ring inside the plasma to create a properly shaped poloidal magnetic field can be circumvented by using a high-current beam of relativistic electrons in place of the ring. Such a beam would not be a sink for plasma; in fact, it would serve to heat the plasma. For example, one might conceive of replacing the ring of a spherator (Fig. 9-12) by a beam from one of the presently available relativistic electron beam generators capable of producing short 10^6-A pulses at 1 MeV. The major problem is how to inject and trap the electrons.

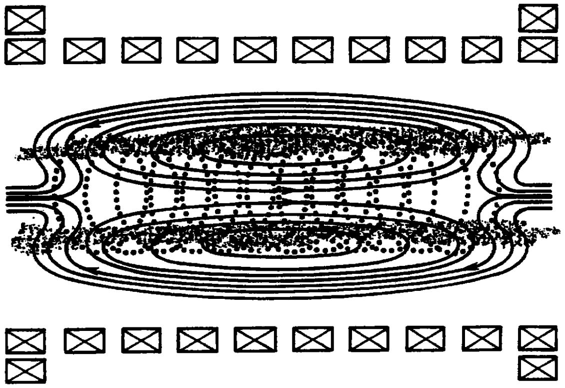


FIGURE 9-13 In the Astron, a layer of relativistic electrons (dots) encircling the horizontal axis of symmetry is confined by a mirror field. The electron current distorts the mirror field into the shape shown, which has a stable confinement region with closed lines of force. The relativistic electrons also serve to heat the plasma in this region.

A very large machine of this type, called the Astron, was built at the Lawrence Livermore Laboratory in California. Figure 9-13 shows a diagram of it. The 4-MeV electrons from an accelerator were injected into a magnetic field with mirrors at the ends. The gyrating electrons produce a field opposed to the confining field, and if the electron current were large enough, some of the field lines would form closed loops within the plasma, creating a multipole-type poloidal field with an average magnetic well. Adding a current along the major axis to give shear would make the topology identical to that of a spherator. (To compare Fig. 9-13 with Fig. 9-12, rotate one or the other by 90°.) In spite of the fact that 600 A of 6-MeV electrons were ultimately injected into Astron, the current was still insufficient to reverse the magnetic field on the axis; and the experiment has been discontinued.

Relativistic beam machines can be considered as being intermediate between tokamaks and multipoles. In all cases, a toroidal current is needed to produce a poloidal magnetic field. In tokamaks, the current cannot be made too large because of the kink instability. In multipoles, the solid rings cannot kink, but they interfere with the plasma. Relativistic beams are not as stable as solid rings, but they have a higher degree of rigidity than plasma electrons because of the relativistic increase in mass.

The principle of magnetic mirror confinement was discussed in Section 2.3.3. The simple mirror geometry shown in Fig. 2-8, however, is unstable against the gravitational flute instability, because the curvature is everywhere convex, so that the centrifugal force is directed in the opposite direction to the density gradient (cf. Eq. [6-55]). To achieve stability, an auxiliary current along so-called *Ioffe bars* can be used. Figure 9-14 shows how the plasma is distorted into an asymmetric shape when these windings are added. The plasma then finds itself in an *absolute magnetic well;* that is, the field strength $|B|$ increases in every direction, radial as well as axial. Such a minimum-$|B|$ configuration is stable against the low-frequency modes that plague toruses, but, as we shall see, has other instabilities. In a torus, the best that can be achieved is a shallow *average* magnetic well, the average being taken along a line of force. Instabilities could still occur locally in regions of unfavorable curvature.

A further refinement of the configuration of Fig. 9-14 is to combine the Ioffe bars and the main coils into a single winding. The resulting

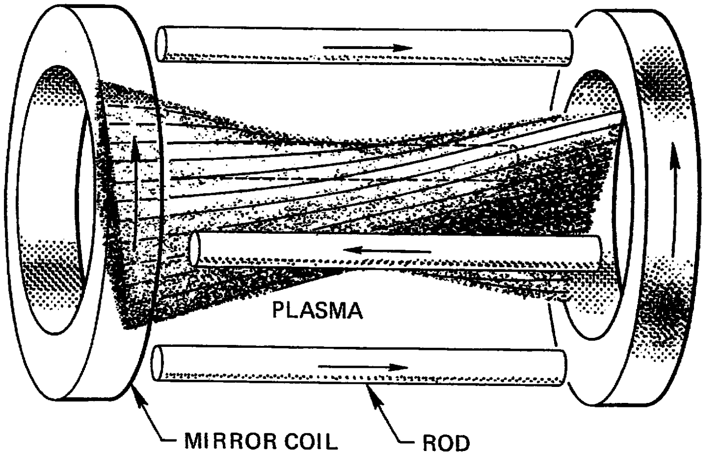


FIGURE 9-14 A magnetic mirror can be made into a minimum-|**B**| configuration by the addition of four Ioffe bars—rods carrying current in alternate directions. The plasma is then distorted into the shape shown and is stable against gravitational instabilities. [From *Scientific American* **215**, 21 (1966).]

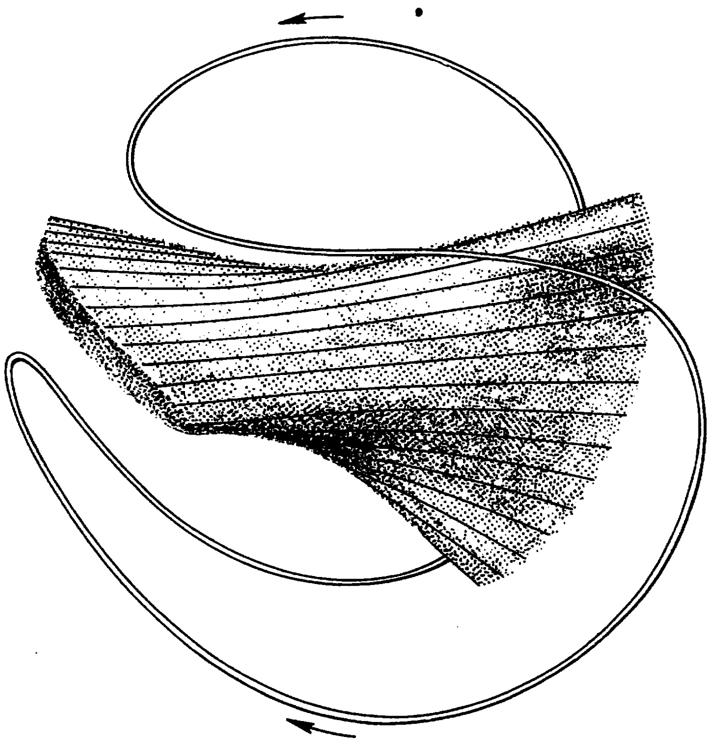


FIGURE 9-15 **A "baseball coil" is topologically equivalent to a simple mirror with Ioffe bars.** [From *Scientific American, loc. cit.*]

winding has the shape of the seam on a baseball and is called a *baseball coil* (Fig. 9-15). Figure 9-16 shows a superconducting baseball coil being lowered into its vacuum chamber at the Lawrence Livermore Laboratory. The plasma is formed by the Lorentz ionization of an energetic beam of neutral hydrogen atoms injected into the magnetic field. Figure 9-17 shows a drawing of the entire system.

The best results so far have been obtained with a larger mirror device, the 2XII, also at Livermore. Figure 9-18 shows a schematic of this. The plasma is injected, heated by adiabatic compression, and then further heated by injection of a beam of energetic neutral atoms, which charge-exchange with the ions. In this manner, ion temperatures of about 8 keV, densities of order 6×10^{13} cm^{-3}, and confinement times of order 0.5 msec have been achieved, though not simultaneously.

Mirror machines are basically steady state devices, in which the rates of injection and diffusion loss are balanced. The diffusion is mainly out the ends, since the magnetic well prevents instabilities that give rise to Bohm diffusion radially. The diffusion out the ends is not ordinary diffusion, however; it is diffusion in *velocity space*. Particles outside the loss cone (Fig. 2-9) can diffuse into the loss cone by making a small-angle collision. Instabilities can lead to enhanced velocity-space diffusion, but only if the frequency is higher than Ω_c, so that the ion adiabatic invariant can be broken (Section 2.8.1). Velocity-space in-

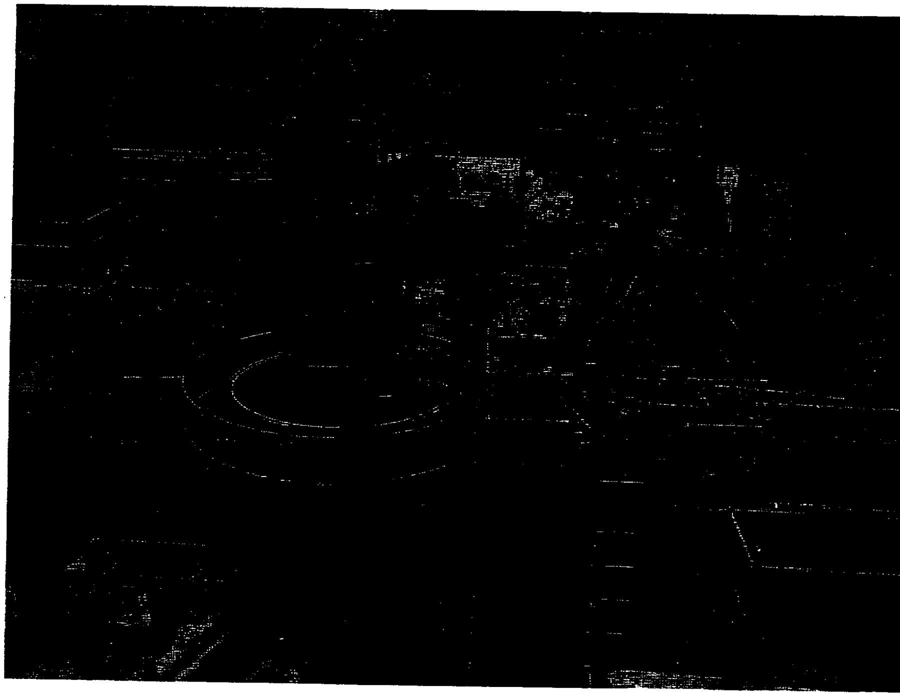


FIGURE 9-16 **The Baseball II superconducting coil being lowered into its vacuum tank at the Lawrence Livermore Laboratory, California.** [Sponsored by the U.S. Atomic Energy Commission.]

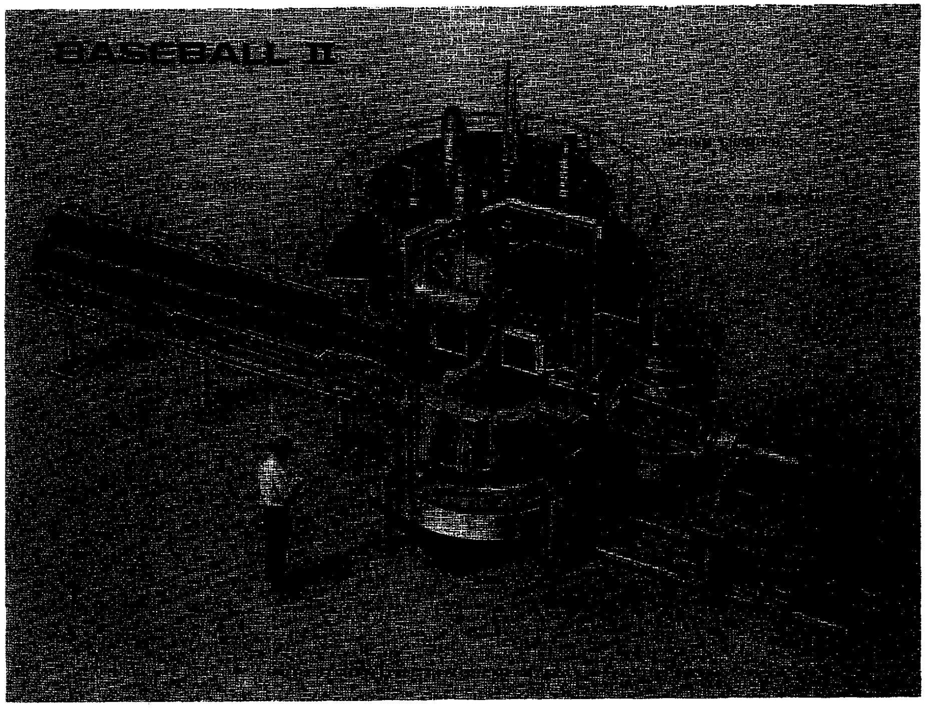
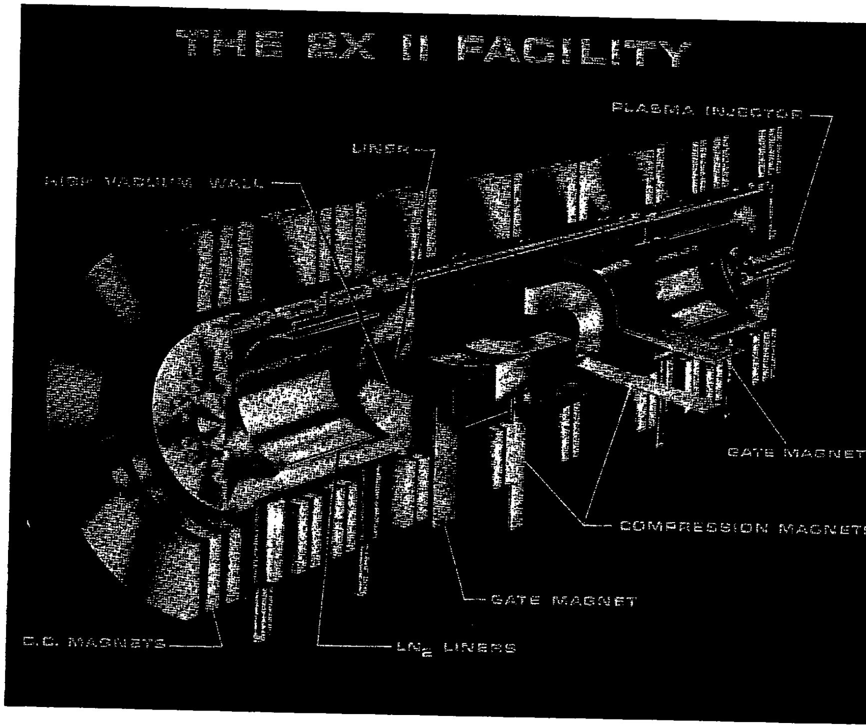


FIGURE 9-17 **The plasma in Baseball II is produced by the self-ionization of a fraction of an intense beam of neutral hydrogen injected across the magnetic field.** [Lawrence Livermore Laboratory, sponsored by the U.S. Atomic Energy Commission.]

stabilities driven by the deviation of a loss-cone distribution (Fig. 7-7) from a Maxwellian are just in the right frequency range, unfortunately. Such instabilities are less likely to arise if the machine is short (as it is in baseball geometry) and if the injected velocity distribution has a large spread. Theoretical understanding of the observed rate of diffusion in terms of the nonlinear level of unstable oscillations has begun to emerge.

In ordinary diffusion, only the particles near the edge can leave the system by making a collision. Velocity-space diffusion is much more dangerous because it can occur anywhere in the entire volume. Once a particle is scattered into the escape cone, it leaves upon the next arrival at a mirror throat. Because of this, mirror devices tend to have a relatively fast loss rate; to minimize this, mirror reactors are usually designed with higher KT and lower density than toroidal reactors.

Direct conversion is a clever scheme by which the end loss can be turned into an advantage. Plasma streaming out the ends is first spread by a diverging magnetic field until the density is low enough and the Debye length long enough that electric fields can penetrate into the plasma. The electrons are separated from the ions by a sharp bend in the magnetic field, which the ions cannot follow. The ion beam is then decelerated by a series of electrodes at progressively larger positive



The 2XII device at the Lawrence Livermore Laboratory is a large magnetic mirror produced by "yin-yang" coils, a modification of a baseball coil. The plasma is injected by plasma guns, adiabatically compressed, and then further heated by neutral beam charge exchange. [Lawrence Livermore Laboratory, sponsored by the U.S. Atomic Energy Commission.] FIGURE 9-18 potentials. The electrode potentials are actually alternating, so as to provide a strong-focusing effect and prevent ions from leaving until they have lost almost all their kinetic energy. When an ion has been slowed down until it no longer feels the strong-focusing force, it leaves radially through a grid and maintains the charge on the electrode on which it is collected. The electrode then can be connected in such a way as to provide dc power. Figure 9-19 shows computed particle trajectories in a direct conversion system. If an efficiency of >90% can be achieved in recovering the charged-particle energy directly as electricity, the Lawson criterion for mirror reactors can be diminished significantly.

9.4 PINCHES

A pinch is fundamentally the simplest of fusion devices: A plasma carrying a current is confined by the magnetic field of the current itself. There are two complementary geometries, the *z*-pinch and the θ-pinch (Fig. 9-20). As the current rises, the increasing magnetic field compresses the plasma and heats it; confinement and heating occur together. Since large currents are needed, pinches operate only in short pulses. A θ-pinch usually has a magnetic mirror configuration to diminish end losses. Alternatively, either type of pinch can be bent into a torus.

The current needed to confine a thermonuclear plasma is easily computed in the case of the *z*-pinch. The magnetic pressure $B_G^2/8\pi$ must be sufficient to balance the plasma pressure nKT. If I is the total current in a column of radius r, the field at the surface is $B_G = 2I/cr$, where I is in esu, or $B_G = I/5r$, where I is in amperes. Let $N = \pi r^2 n$ be the number of ions per cm length. The balance of pressures then gives

$$\frac{1}{8\pi}\left(\frac{I}{5r}\right)^2 = \frac{NKT}{\pi r^2}$$

or

$$I^2(\mathrm{A}) = 200NKT \qquad [9\text{-}10]$$

This is known as the *Bennett pinch condition.* When the hundreds of thousands of amperes that are needed are supplied, the plasma is subject to the kink instability (Fig. 9-3) or the *sausage instability*, a related phenomenon in which the distortion is a local narrowing of the cross section. Although various schemes to suppress these instabilities have been tried, none of them is completely successful.

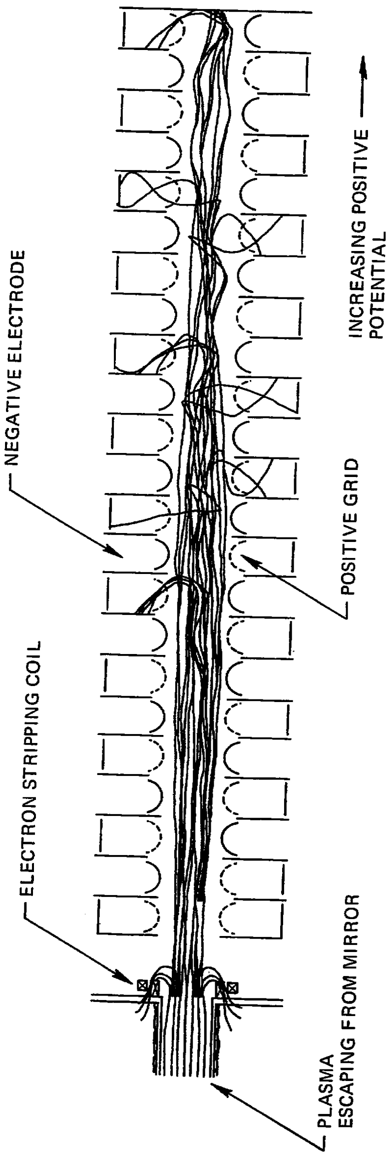


FIGURE 9-19 **Computed ion trajectories in a proposed electrostatic decelerator for direct conversion of the kinetic energy of charged fusion products to electricity.** [Courtesy of R. F. Post, Lawrence Livermore Laboratory, sponsored by the U.S. Atomic Energy Commission.]

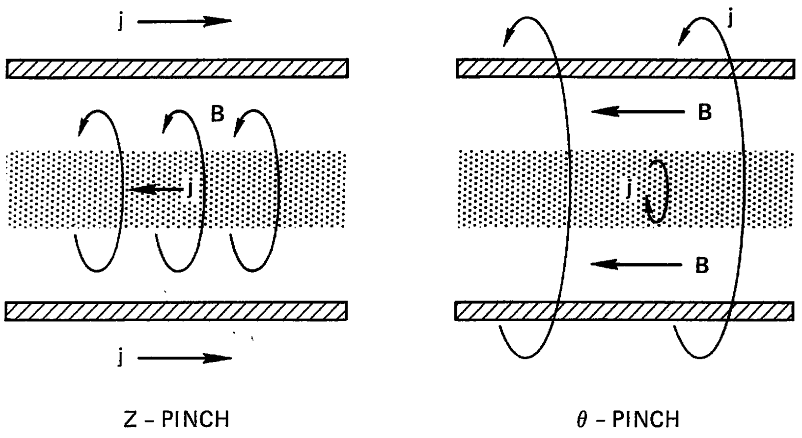


FIGURE 9-20 **Geometry of a *z*-pinch (left) and a θ-pinch (right).**

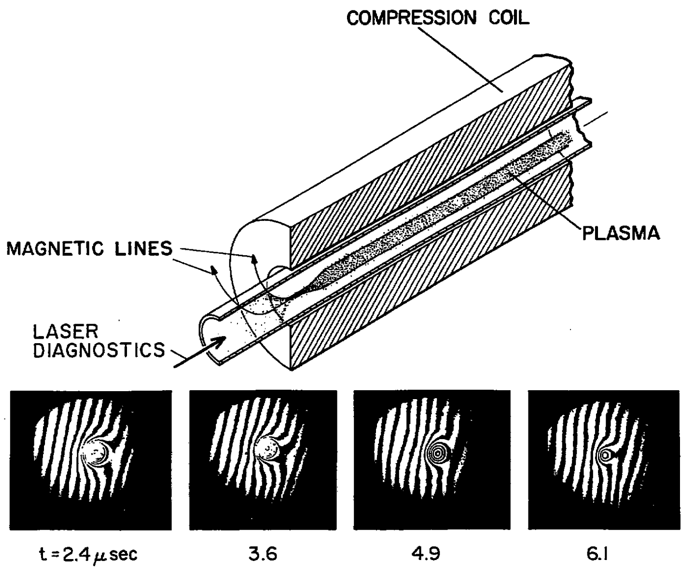


FIGURE 9-21 **Diagram of a linear θ-pinch. The laser interferograms below it show that the plasma decays in density with time but remains stably confined.** [Los Alamos Scientific Laboratory, sponsored by the U.S. Atomic Energy Commission.]

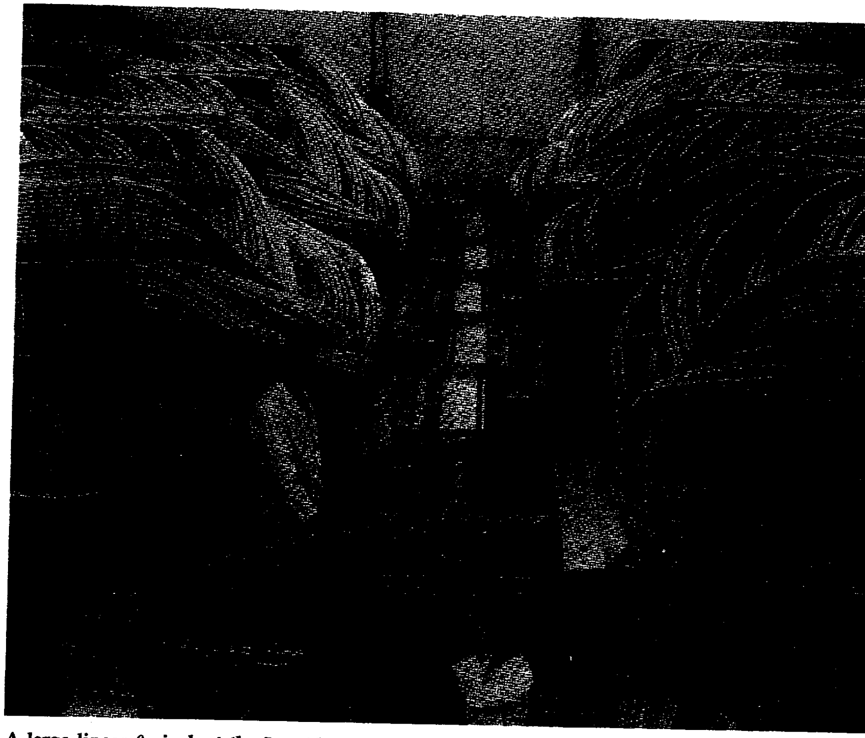


FIGURE 9-22 **A large linear θ-pinch at the Los Alamos Scientific Laboratory in New Mexico. The energy required to pulse the coil is stored in fast capacitors filling the building and connected by the cables shown.** [Los Alamos Scientific Laboratory, sponsored by the U.S. Atomic Energy Commission.]

The θ-pinch, on the other hand, shows a remarkable degree of stability. Figure 9-21 shows axial views of the density distribution taken with a laser interferometer. The circular fringes indicate lines of constant plasma density. It is seen that the plasma does not migrate to the walls as it decays. Densities up to 10^{17} cm^{-3}, temperatures of several kilovolts, and confinement times of several microseconds have been achieved in θ-pinches. At these densities, the collision rate is so high that mirror confinement is not efficient. Long, linear θ-pinches have been constructed to increase the time of flight of ions to the ends. Figure 9-22 is a photograph of the long θ-pinch at Los Alamos Scientific

Laboratory in New Mexico. The capacitor banks needed to energize the pinch coil fill a large building. Classical diffusion has been observed in θ-pinches. Figure 9-23 shows the measured density profile of an 8-m-long θ-pinch at the Culham Laboratory in England. The profile agrees much better with the one calculated for classical diffusion than with the one for Bohm diffusion. Although the fluctuation level has not been measured (it is difficult to probe such high-density plasmas), it is clear that instabilities do not play a major role.

To avoid end losses, a θ-pinch can be bent into a torus. Figure 9-24 shows a 120° sector of the Scyllac machine at Los Alamos, which will test the toroidal θ-pinch concept. Feedback stabilization will be used to help suppress toroidal instabilities. Since θ-pinches operate only at high β, the problem of plasma heating will be automatically solved. Whether or not Scyllac will suffer from the same troubles as other toruses remains to be seen. Relatively little theory has been done on the equilibrium and stability of θ-pinches, and the hope for success in this approach to fusion rests primarily on experimental evidence gained with linear pinches.

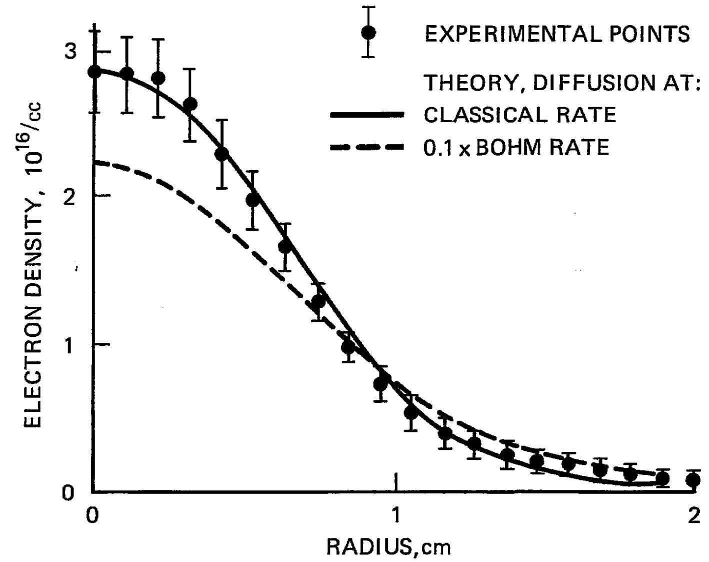
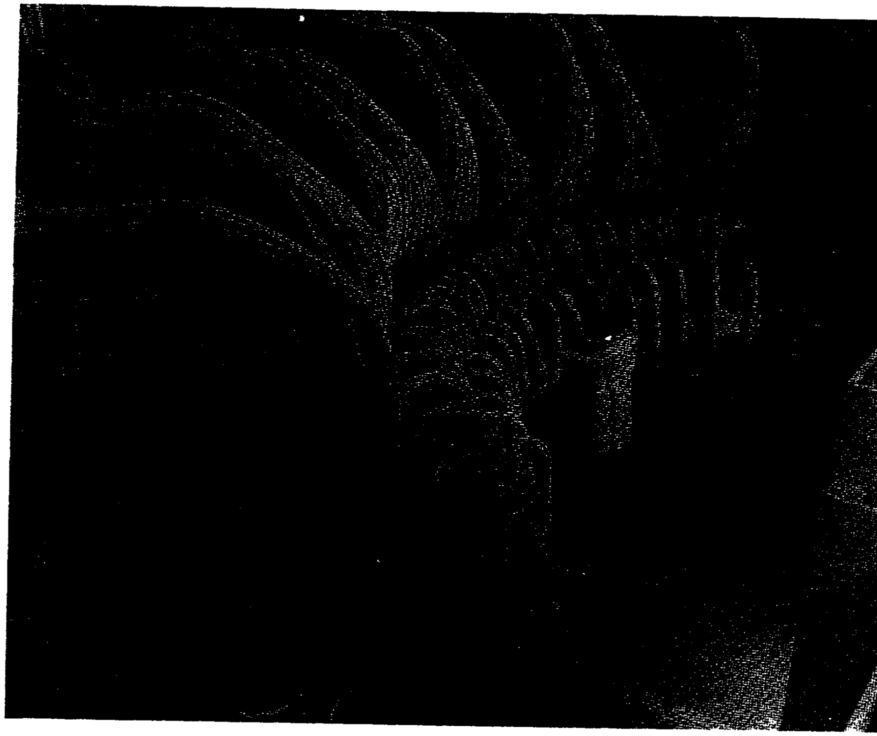


FIGURE 9-23 **Measurements of the density profile in an 8-meter-long θ-pinch, demonstrating that losses are controlled by classical collisional diffusion. The solid curve is computed on the basis of the Fokker–Planck equation. The dashed curve is ten times the value expected if Bohm diffusion had been operative.** [H. A. B. Bodin *et al.*, *Plasma Physics and Controlled Nuclear Fusion Research* **II**, 533 (1968) (International Atomic Energy Agency, Vienna, 1969).]



A 120° sector of a toroidal θ-pinch called Scyllac at Los Alamos. [Los Alamos Scientific Laboratory, sponsored by the U.S. Atomic Energy Commission.] FIGURE 9-24

A θ-pinch is a pulsed device. In a reactor, the energy used to form and compress the plasma in each pulse would have to be recovered efficiently and stored between pulses. Inductive storage in superconducting coils cooled to liquid He temperatures could be used to do the job. Direct conversion of fusion energy to electricity occurs naturally in such a system, since the charged reaction products would make the plasma expand with more energy than was used to compress it.

9.5 LASER-FUSION

Pulsed infrared lasers can produce prodigious power densities, and it is natural to try to use them to ignite a fusion reaction. However, as with the other approaches, the road to nirvana is not straightforward. The two most powerful lasers are the following:

Lasing medium	Wavelength, μm	Cutoff density n_c, cm^{-3}
Nd-glass	1.06	10^{21}
CO_2	10.6	10^{19}

The critical density $n_c = m\omega^2/4\pi e^2$ is that at which $\omega = \omega_p$. Since the laser radiation cannot propagate at plasma densities higher than this, we shall find that the parameter n_c plays a crucial role. As an example of the instantaneous power available, we note that a Nd-glass laser can deliver 250 J in 0.1 nsec, or 2.5×10^{12} W. This figure is equal to six times the entire electrical output capacity of the United States.

Two different ways have been proposed to achieve laser-fusion. In laser-gas-fusion, a CO_2 laser beam is used to ionize and heat a long column of gaseous deuterium and tritium at a density of about 10^{17} cm^{-3}. The laser light is absorbed by the process of *inverse bremsstrahlung,* which is simply the resistive damping of the light wave due to electron–ion collisions. Since the collision frequency varies as $KT_e^{-3/2}$ (Eqs. [5-69] and [5-70]), this process is quite inefficient at thermonuclear temperatures; and, for $n \ll n_c$, the absorption length would be measured in kilometers. However, nonlinear parametric processes (Section 8.5) are expected to occur at large intensities, and these can increase the absorption and reduce the plasma length to reasonable dimensions. To satisfy the Lawson criterion at $n = 10^{17}$ cm^{-3} would require magnetic confinement.

In laser-pellet-fusion, the laser light is focused onto a small pellet of solid DT, which has a density n_0 of about 5×10^{22} cm^{-3} and a mass density $\rho_0 = n_0 M$ of 0.2 g/cm³. Since n_0 is much larger than n_c even for a Nd-glass laser, the radiation is reflected as soon as a plasma of density 10^{21} cm^{-3} is formed on the surface of the pellet. One depends on anomalous absorption by the parametric decay instability (Section 8.5.6) to ionize the rest of the pellet and heat it to 10 keV. At densities of order 10^{22} cm^{-3}, it is impossible to create a magnetic field strong enough to balance the plasma pressure nKT. The reaction must occur in a micro-explosion lasting less than 10^{-10} sec. The velocity at which a plasma expands is determined by the ion inertia and the plasma potentials (of order KT_e) available to accelerate the ions. Consequently, the expansion velocity is scaled to the acoustic velocity $v_s = (KT_e/M)^{1/2}$; and the confinement time τ is given by $\tau \approx R/v_s$, where R is the pellet radius. When this value is used together with reasonable estimates of the efficiencies involved, a Lawson criterion on $n\tau$ for laser-fusion is obtained. This criterion is usually expressed as

$$\rho R > 1 \quad g/cm^2 \qquad [9\text{-}11]$$

To satisfy this with $\rho = \rho_0$ would require a laser pulse larger than 3×10^{10} J, beyond the realm of credibility.

A possible solution is to compress the pellet to $\rho = 10^4\rho_0$. At intensities above 10^{15} W/cm², the radiation pressure is of the order of 10^6 atm. This is, however, insufficient to accomplish the compression. Figure 9-25 illustrates the proposed scheme. The pellet is irradiated by laser beams from all directions. The laser energy is absorbed by parametric processes at the critical layer, and a plasma shell is heated. The shell then expands, and its momentum is used to compress the central core, which comprises 10% of the original pellet. Fusion then occurs in the core, and the energy released is captured in a surrounding bath of liquid lithium. The energy required to heat a pellet is proportional to its mass $\rho(4/3)\pi R^3$. If Eq. [9-11] is satisfied and $R = \rho^{-1}$, the laser

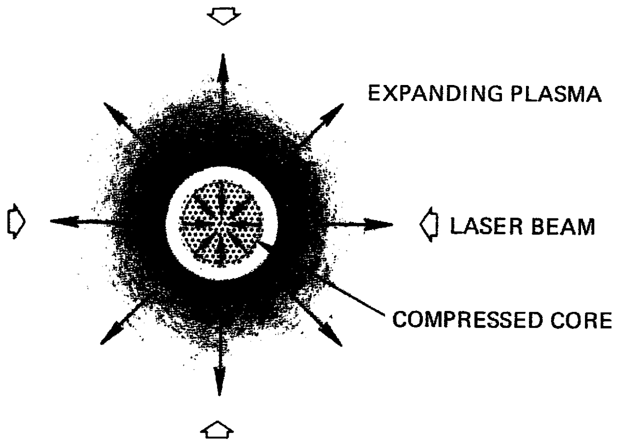


FIGURE 9-25 The scheme of producing fusion by laser heating of a pellet of solid DT involves symmetrical heating of a plasma shell by converging laser beams (outermost arrows), expansion of the heated shell (long arrows), and compression of the core (innermost arrows) by the recoil.

energy is proportional to ρ^{-2}. Thus, a reduction of 10^8 is achieved by compressing by a factor 10^4. The required pulse energy is reduced to a realistic value below 1 MJ.

A number of problems remain to be solved. The laser energy must be delivered in a sufficiently short time. The incident radiation must be sufficiently isotropic to avoid Raleigh–Taylor instabilities. The shape of the pulse in time must be such as to preheat the core to the proper temperature before adiabatic compression. If the temperature is too high, the compressed density will be too low; if the temperature is too low, ignition temperature will not be reached. The electrons heated in the parametric instability must not be so fast as to penetrate the core and preheat it. Other parametric instabilities, such as backscattering, must not cause the light to be reflected before reaching the critical $\omega = \omega_p$ layer. The efficiency and repetition rate of lasers, as well as their energy, must be greatly increased. The development of shorter-wavelength lasers (for instance, Xe), with a higher value of n_c, would ease these problems. Although the difficult problems of magnetic confinement are obviated in laser-pellet-fusion, the new problems are themselves quite formidable.

9.6 PLASMA HEATING

Theoretical understanding of how energy is absorbed by a plasma and converted into random thermal motions is still in a relatively primitive stage, partly because of the nonlinear nature of the problem, and partly because it is difficult to disentangle heating effects from confinement effects in experiments. Listed below are some of the many ways a plasma may be heated.

1. *Ohmic heating.* This is simply the I^2R Joule heat dissipated by a current in a resistive plasma. Ohmic heating is the primary method used in stellarators and tokamaks.

2. *Adiabatic compression.* This is the primary method used in some mirror machines, in θ-pinches, and in laser-pellet-fusion. Recently, it has also been applied to tokamaks (Fig. 9-9).

3. *Ion wave heating.* The first type of rf heating tested was ion cyclotron resonance heating (ICRH). An electromagnetic ion cyclotron wave is excited by an rf coil surrounding the plasma in a region where $\omega < \Omega_c$. The wave propagates into a decreasing B field (a "magnetic beach") where the resonance condition $\omega = \Omega_c$ is attained, and the wave energy is absorbed by the ions by cyclotron acceleration. The fast hydromagnetic wave, related to the magnetosonic mode of Section 4.19, can also be used. Promising results have also been achieved with waves related to the lower hybrid oscillations of Section 4.11.

4. *Electron wave heating.* Using high-powered microwave tubes, one can accelerate electrons at their cyclotron frequency in the GHz range. This is called electron cyclotron resonance heating (ECRH). Although very large electron energies can be produced this way, the energy is usually not thermalized but remains in a small number of "perpendicular runaway" electrons. A lower-frequency source can produce nonresonant heating by resistive dissipation. A combination of resonant and nonresonant waves gives the best result, possibly because of wave–wave coupling effects. Note that electron heating is not useful in itself; for fusion purposes, the energy must eventually be transferred to the ions.

5. *Charged particle injection.* Mirror devices and multipoles are often filled with plasma from plasma "guns." These are capable of injecting ions and electrons at kilovolt energies by $\mathbf{j} \times \mathbf{B}$ acceleration. Accelerators can produce 300-keV ion beams or 6-MeV electron beams of sufficient density to be of interest for plasma heating. Such particles have large enough Larmor radii to cross the magnetic field.

6. *Neutral beam injection.* It is possible to produce intense beams of neutral hydrogen or deuterium at 10^4 eV or above by neutralizing an accelerated ion beam in a gas cell. The neutral particle can enter a magnetic field and charge-exchange with a cold ion in the plasma, leaving behind a fast ion and a slow neutral atom, which then escapes. This method is used for both mirrors and toruses. When used in a torus already filled with plasma, an additional benefit accrues: the charge-exchange ions have enough energy to undergo fusion reactions while they are slowing down and heating the plasma. This results in a reduction of the Lawson criterion. In the "two-component torus" (TCT) concept, neutral beams of tritium injected into a 2-keV deuterium plasma, or vice versa, are used to achieve energy breakeven although the ohmically heated plasma is below the ignition temperature (Fig. 9-26).

7. *Magnetic pumping.* An oscillation of the field strength in a local mirror section of a torus can transfer energy to ions if the frequency is such that the adiabatic invariant is broken (cf. Section 2.8.1).

8. *Beam–plasma interactions.* Injection of a beam of fast electrons or ions into a plasma can cause a two-stream instability (Section 6.6). The directed beam energy is converted into wave energy, which must then be converted to particle energy by Landau damping or parametric processes. Electron beams can be made to couple more effectively to ions by modulating at a low frequency or injecting at an angle to the

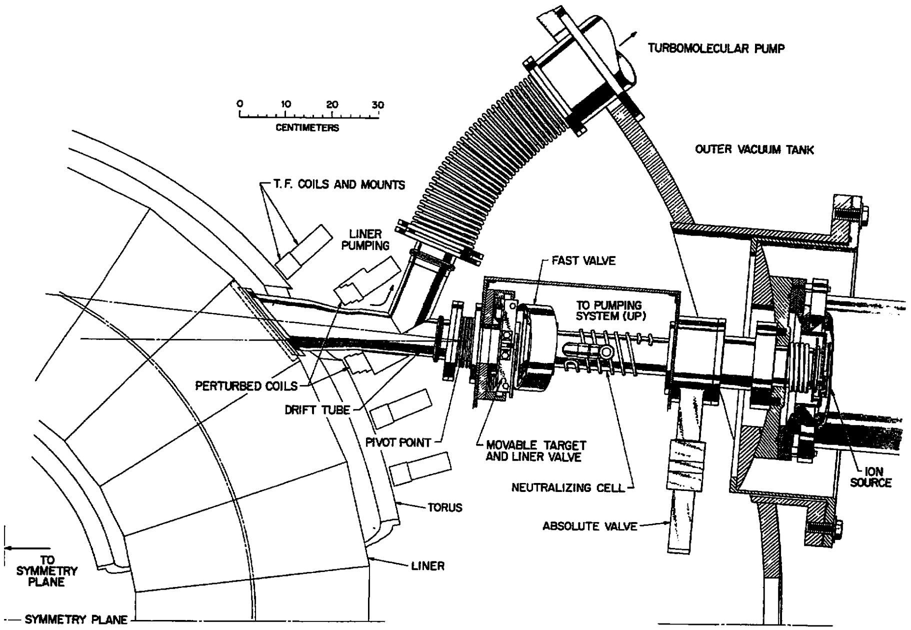


FIGURE 9-26 **ORMAK injection system: Schematic of a neutral beam injector for heating a tokamak plasma by charge exchange between the fast neutral atoms injected and the relatively slow ions of the cold plasma. As the resulting fast ions thermalize with the main body of the ion distribution, they can undergo fusion reactions in the process. These reactions constitute a bonus not present in other heating methods and are the primary feature of the "two-component torus" (TCT) concept.** [Courtesy of the Oak Ridge National Laboratory, operated by the Union Carbide Corporation under contract with the U.S. Atomic Energy Commission.]

magnetic field. The availability of megampere relativistic electron beams has increased interest in this heating method. However, there is always the problem of how to inject electrons into a magnetic field.

9. *Turbulent heating.* It has been demonstrated experimentally that inducing a fast-rising electron current in a plasma causes a turbulent state with a broad spectrum of electric field fluctuations. Electrons are slowed down by these random electric fields rather than by collisions with ions. Ohmic heating then occurs with an *anomalous resistivity* even though Coulomb collisions are negligible. Although much of the experimental work has been done on linear mirror machines, turbulent heating is a potentially important method for heating tokamaks.

10. *Parametric wave heating.* Intense microwave or infrared laser beams do not couple directly to resonant particles, because of the disparity between the wave's phase velocity and the particles' thermal velocity. Electromagnetic waves can decay parametrically into ion waves, however, and the energy can be transferred to particles by Landau damping.

11. *Field annihilation.* If a magnetic field has a stagnation point, as in a multipole (Fig. 9-10) or in the magnetospheric tail of the earth, magnetic energy can be converted into particle energy by large induced electric fields. This would obviously be a very economical way to heat a magnetically confined plasma if it could be exploited.

FUSION TECHNOLOGY 9.7

Even after the problems of plasma confinement and heating have been solved and the scientific feasibility of a controlled fusion reaction demonstrated, a large number of technological problems will remain to be solved before fusion reactors can be built. Some of these problems are listed below.

1. *Wall materials.* The vacuum wall exposed to the plasma must be made of a material that is easy to fabricate, can withstand high temperatures, is not damaged by a large flux of 14-MeV neutrons or by sputtering by charged particles, and is not transmutable into long-lived radioactive products. Among known materials, niobium meets these specifications best, but it becomes highly radioactive, and storage of used wall material becomes a problem.

2. *Lithium blanket.* The blanket serves the dual purpose of breeding tritium via the reaction of Eq. (9-2) and of capturing the thermal energy of the neutrons produced in the fusion reaction. Although Li is a good coolant, there are severe problems of corrosion and of pumping liquid metals across magnetic fields.

3. *Magnet design.* The magnetic structure will require large amounts of superconducting material and a large cryogenic system for cooling it. The windings have to be supported against enormous magnetic stresses.

4. *Fuel injection and recovery.* Injecting deuterium and tritium into a torus is not a trivial problem. Since only a small fraction of the tritium reacts during a confinement time, it must be recovered very efficiently in the vacuum system. In a steady-state reactor, there is the problem of extracting the products of the reactions, such as He and H.

5. *Environmental hazards.* Besides the radioactivity induced in the structural materials by the neutrons, there is the important problem of tritium leakage. Although all the tritium produced will be consumed, there is a sizable inventory of tritium on a reactor site, and its dispersal into the water supply by accident or into the atmosphere by diffusion is an important problem.

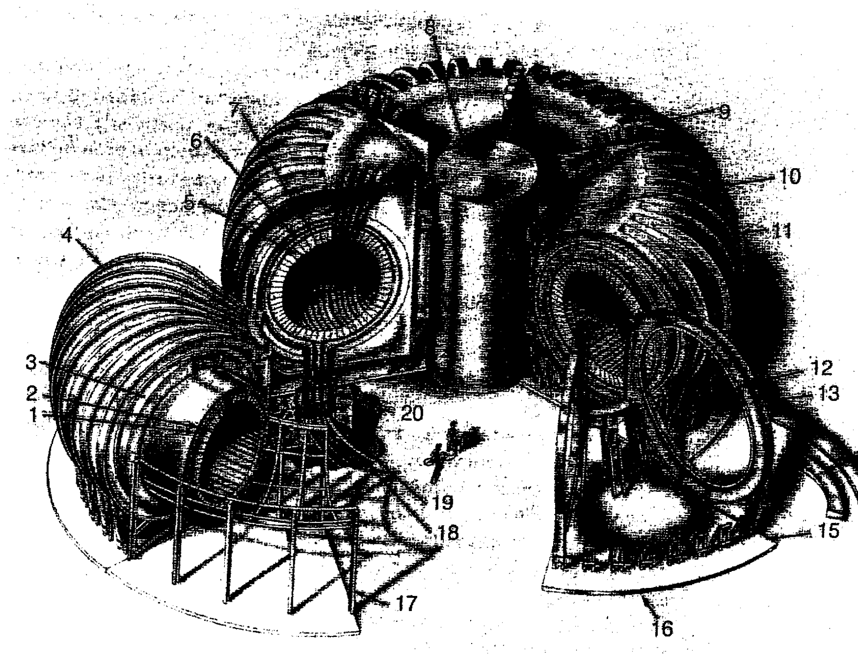
6. *Fission–fusion hybrid reactors.* The Lawson criterion can be lowered by combining a fission reactor with a fusion reactor and making use of the fusion-produced neutrons to help with the fission process. This may very well be the first practical use of controlled fusion.

These are but a small sample of the tasks ahead. The scope of the field of fusion technology can be imagined when one realizes that each magnetic device described previously, each heating method, and each energy conversion method will have to undergo years of engineering development before it becomes a practical reality. Engineering designs have only recently begun. Figure 9-27 is a drawing of a tokamak reactor designed at the Oak Ridge National Laboratory in Tennessee and will give the reader an idea of what a fusion reactor will look like.

SUMMARY 9.8

The search for a stable magnetic confinement device, which has occupied plasma physicists for over two decades, has narrowed down to three main configurations: the tokamak, the minimum-B magnetic mirror, and the toroidal θ-pinch. The tokamak still requires an understanding of electron energy containment, an auxiliary heating method, and a test of stability at high β. The magnetic mirror requires an understanding of the observed confinement, tests at high β, and a large-scale test of the efficiency of direct conversion. The θ-pinch faces a crucial test of stability in a toroidal configuration.

The next stage in the advance toward demonstration of the scientific feasibility of controlled fusion is the development of new heating methods and the theoretical clarification of the heating process. A series of larger machines will test scaling laws based on our present understanding of instabilities and confinement. The problems of fusion technology will remain to be solved after plasma confinement



Toroidal Fusion Reactor (1000 MWt)

1. Potassium Boiler Feed Pipes
2. Potassium Vapor Pipes
3. Magnet Shield
4. Sextant (Nearly Assembled)
5. Blanket Segments
6. Potassium Vapor Outlet Manifold
7. Potassium Boiler Feed Manifold
8. Poloidal Magnet Core
9. Neutral Beam Injectors
10. Compression Rings
11. Thermal Insulation On Magnet
12. Magnet Coil
13. Magnet Reinforcing Ring
14. Blanket Segments
15. Sextant Support Grid
16. Sextant, Early In Assembly Proc
17. Assembly Jig For Blanket Struct
18. Potassium Feed Pipe
19. Potassium Vapor Pipe
20. Duct To High Vacuum Pump

Artist's conception of a design study of a 1000 MW-thermal tokamak reactor cooled by potassium vapor and utilizing superconducting magnets. The cellular structure in the interior is the lithium blanket. [A. P. Fraas, Oak Ridge National Laboratory, operated by Union Carbide Nuclear Division for the U.S. Atomic Energy Commission.] **FIGURE 9-27**

has been achieved. The engineering of a reactor cannot take place until the magnetic configuration has been specified.

It is likely that many of the confinement concepts will be combined in the final product. Minimum-$\bar{B}$ stabilization can be added to shear stabilization in toruses, possibly by the use of relativistic electron beams. Local mirror regions in toruses may be created in order to take advantage of neutral-beam injection. Even in an ordinary torus, trapping in local mirrors may be an important phenomenon. Conversely, mirror devices may be connected in a ring to cut down end losses. Shock heating added to a torus will make it resemble a θ-pinch, which, in the Scyllac configuration, is just a high-β torus.

Although there has been steady progress toward the Lawson criterion and the ignition temperature in experiments, the real progress may be said to lie in the development of the solid foundations of plasma physics. Success in understanding the complex behavior of plasmas has been demonstrated, for instance, in the agreement between theory and experiment in minimum-B stabilization and neoclassical diffusion. The mathematical techniques and physical intuition of plasma physicists now enable them to analyze and understand relatively quickly the new results from experiments. The basic linear theory of plasmas has reached textbook status, but the quest for fusion energy remains an unclosed chapter.

APPENDIX

I. UNITS

The units used in this book are cgs electrostatic units. This system differs from the commonly used cgs Gaussian units in only one minor respect. Maxwell's equations for vacuum and Newton's third law in these two systems are as follows:

cgs-esu	cgs-Gaussian
$\nabla \cdot \mathbf{E} = 4\pi e(n_i - n_e)$	$\nabla \cdot \mathbf{E} = 4\pi e(n_i - n_e)$
$\nabla \times \mathbf{E} = -\dot{\mathbf{B}}$	$c\nabla \times \mathbf{E} = -\dot{\mathbf{B}}_G$
$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B}_G = 0$
$c^2\nabla \times \mathbf{B} = 4\pi\mathbf{j} + \dot{\mathbf{E}}$	$c\nabla \times \mathbf{B}_G = 4\pi\mathbf{j} + \dot{\mathbf{E}}$
$\epsilon = \mu = 1$	$\epsilon = \mu = 1$
$m\dfrac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$	$m\dfrac{d\mathbf{v}}{dt} = q(\mathbf{E} + \dfrac{1}{c}\mathbf{v} \times \mathbf{B}_G)$

B without a subscript in this book means that it is measured in esu. When **B** is measured in the usual units of gauss, it is denoted by $\mathbf{B}_G$. It is clear from the above equations that the two systems are identical if **B** is identified with $\mathbf{B}_G/c$. All the other quantities are unchanged.