# Alternate concepts in magnetic fusion

Despite the success of the tokamak for plasma confinement, the alternative magnetic configurations are still in the running for commercial fusion reactor development.

Francis F. Chen

The tokamak is a marvelous device for plasma confinement, but can it be made into a commercially viable reactor? This is a question being asked more and more often by the electric utilities and the informed public. As a magnetic container of hot plasma, the tokamak is without peer. Now that the complicating factor of impurity radiation has been removed, the self-healing properties of the tokamak discharge, leading to good confinement scaling in both the collisional (MIT Alcator) and the collisionless (Princeton Large Torus) regimes, have become apparent. But satisfying the temperature, density and confinement time conditions for fusion is only a part of the story. The ultimate users of fusion—the electric utilities—are even more vitally interested in such factors as engineering feasibility, reliability and ease of maintenance, overall efficiency, total plant cost, small plant size, and safety and environmental impact. Since the tokamak was developed from the standpoint of plasma stability, there is concern that it may not be ideal from those other viewpoints. Indeed, there may be room for improvement in the accessibility allowed by a tight torus, in the high technology required for auxiliary heating, fueling, and treatment of wall surfaces, and in the costly equipment needed in breeding and containing tritium. Feasible solutions to these difficult engineering problems have been suggested—but are there better solutions?

There appears to be no dearth of ideas on novel systems that could obviate one or several of the engineering difficulties of tokamaks; whether or not the whole package is an improvement remains to be seen. At the very least, the possible gains are offset by an uncertainty in the physics, since very little experimentation has been done on most of these new concepts. For our purposes here, the alternate concepts are divided into six categories: long linear systems, surface-field systems, high-density systems, particle rings, mirror-torus hybrids and reversed-field systems.

## Long linear systems

Most of the plasma-instability troubles of fusion are caused by the curvature of the magnetic field. Linear reactors would have a uniform field produced by a superconducting solenoid (figure 1), thus avoiding the excitation of all but the weakest instabilities. Of course, the plasma is unconfined in the direction of the magnetic field, so the system has to be extremely long to prevent too rapid an escape out of the ends. Typically, the plasma would be 2 cm in diameter and 1-km long. To heat the plasma to the 5–10 keV temperature (5–10 × $10^7$ K) required for ignition, one could inject various types of beams: $CO_2$ laser beams,[1] relativistic-electron beams,[2] light-ion beams[3] or neutral-atom beams. Charged-particle beams can be produced with up to 85% efficiency in diode sources, but long-pulse $CO_2$ lasers, although much more efficient than nanosecond lasers, are limited to 25% efficiency. In that case, a "staged solenoid," (bottom of figure 1) with a normal-conducting pulsed coil, provides most of the plasma heating by adiabatic compression. Several of these coil and plasma tube assemblies can be fitted inside a large superconducting coil and neutron-absorbing blanket. The pulsed coil also increases the field strength and brings the plasma off the wall, but its cooling requirements and its effect on the spectrum of fusion neutrons greatly restrict the flexibility of design.

The choice among heating schemes depends on more than efficiency: The absorption length must be matched to the length of the machine. In $CO_2$ laser heating, absorption occurs through the classical process of inverse bremsstrahlung, in which the electrons oscillating in the light wave dissipate energy as they collide with ions. Since this loss is proportional to $n_e n_i = n^2$, where $n$ is the plasma density, the absorption length is proportional to $n^{-2}$. On the other hand, the length needed for adequate confinement time $\tau$ is proportional to $n^{-1}$, since Lawson's criterion for ignition is $n\tau$ = constant ($\simeq 10^{15}$ sec per cm$^3$). Thus the absorption length is matched to the machine length if $n$ is high enough, greater than about $10^{17}$ per cm$^3$. To confine the plasma pressure at these densities requires a magnetic field of 25–50 Tesla. In electron-beam heating, absorption occurs through turbulent fields created by streaming instabilities. These lead to an observed anomalous absorption length that is very short and, furthermore, is shorter the lower the plasma density. To take advantage of the efficient absorption, and the low density and magnetic fields possible, one must find a way to reduce the end losses so that a short machine can be used without sacrificing confinement time. The exact mechanism of anomalous absorption is not well known, so that scaling to reactor conditions is uncertain. The best heating method may be with 10-MeV beams of deuterons. Here the absorption length varies as $n^{-1}$ and can easily be matched to the machine length by varying the pitch angle at injection.

Many interesting physics problems have been investigated theoretically and experimentally in connection with the long-solenoid proposal;[1] including trapping the beam with a plasma, propagating a "bleaching wave" in which the head of the beam loses the most energy since it encounters cold plasma, parametric backscattering of laser light, plasma stability and transport in a magnetic field that is distorted by large plasma diamagnetism. If these problems can be solved, linear systems could provide a comparatively simple, accessible and maintainable reactor made of many identical and easily replaceable modules each containing a section of the vacuum

---

Francis F. Chen is professor of electrical sciences at the University of California, Los Angeles.

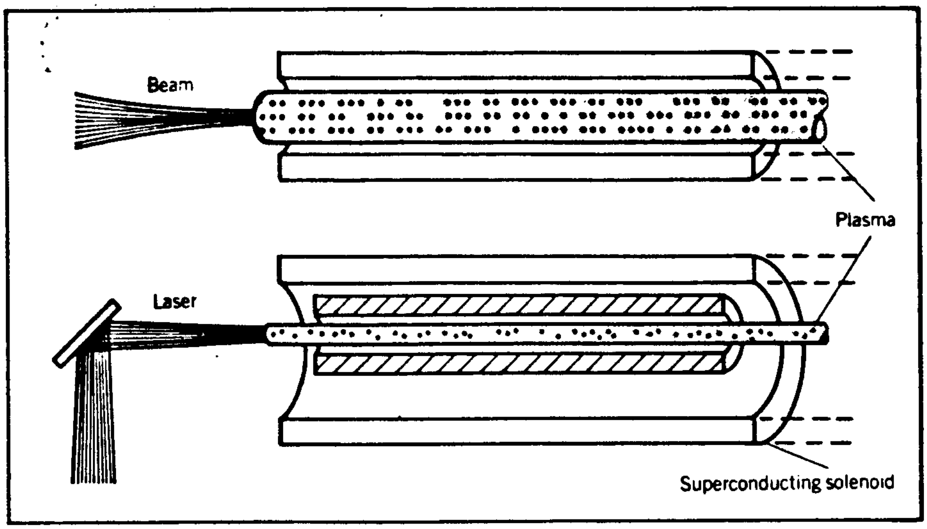
chamber, blanket, and magnet coils. The largest obstacle is the cost of the very long high-field magnet. Present designs for 1000 $MW_e$, He-cooled reactors call for 250 m of 28-T field in the case of $CO_2$ heating, and 190 m of 15-T field in the case of electron-beam heating.

These short lengths are possible only if free-streaming end losses are reduced by factors of 25 (for $CO_2$ heating) and 75 (for electron-beam heating) by some sort of end-stoppering scheme. The two most promising methods are multiple magnetic mirrors and solid endplugs. Multiple mirrors are ripples in the field lines with a wavelength comparable to the mean free path. Particles must diffuse rather than free-stream to the ends, because they are alternately trapped and untrapped by collisions. This scheme has the advantage of being effective also for the alpha-particle products of the D–T reaction. For stability, it is probably necessary to add alternating quadrupole fields, in which case the device resembles a magnet with alternating-gradient focussing. Solid endplugs insulate the plasma from rapid heat loss by forming a layer of dense, cold plasma, which has a low thermal conductivity. The plugs could be made of frozen DT, in which case the particle losses are automatically replenished. The various endplugging schemes afford an opportunity for interesting basic physics experiments.

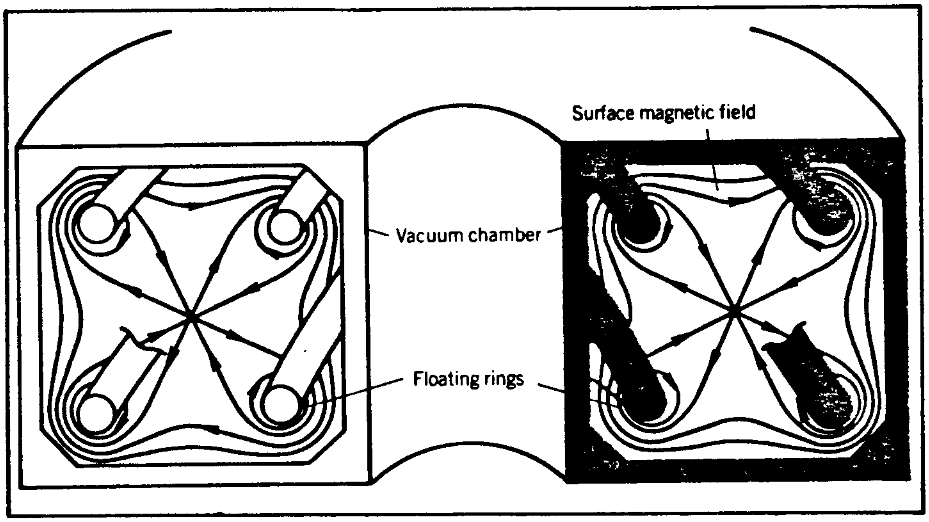
### Surface-field systems

To confine a plasma with a magnetic field, it is not necessary to fill the entire volume with magnetic field—a surface field would do. Since the volume of reacting plasma increases with the cube of the linear dimensions, whereas the field energy increases only as the surface area, surface-field systems would clearly be advantageous at sufficiently large size. Because of the emphasis on small reactors, this reasoning cannot be taken to its logical conclusion. Nonetheless, even moderate-size surface-field devices have a unique feature: the absence of synchrotron radiation losses in the field-free region. This feature could remove a major obstacle to the use of advanced fuel cycles—reactions that do not depend on tritium and do not produce a large flux of 14-MeV neutrons. Such reactions require temperatures exceeding 100 keV ($10^9$ K), which normally entail unacceptably large synchrotron losses.

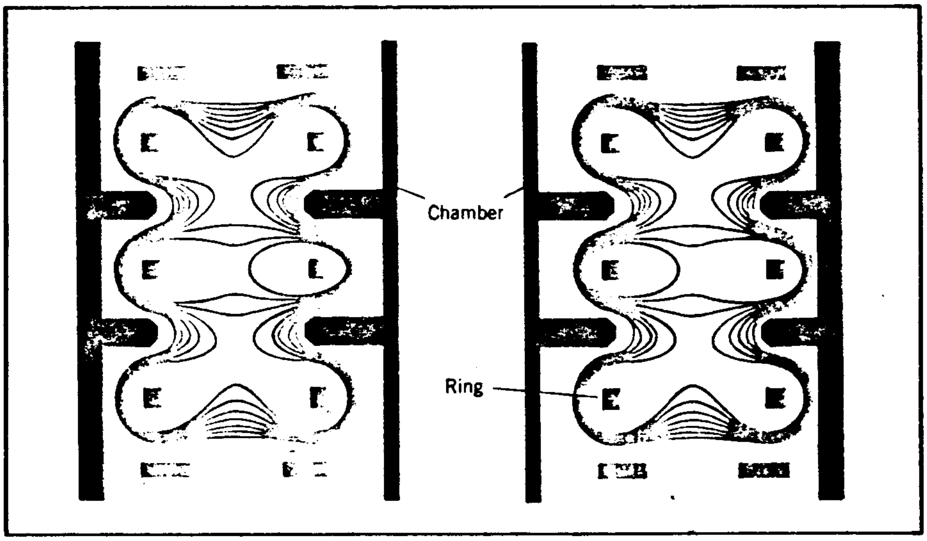
There are basically two ways to produce a surface field: cusps and multipoles. A cusp reactor has a field produced by a stack of circular coils, adjacent ones carrying current in opposite directions. The field lines would curve toward the plasma, and there is an absolute magnetic well; both features lead to good stability. Since the lines of force are not closed, however, there are large particle losses at each cusp. Although recent experiments[4] give encouraging evidence that these



**Long linear systems** confine plasma magnetically in the radial direction and inertially in the axial direction. Particle or light beams are used for heating. In the staged solenoid (bottom) a superconducting solenoid contains one or more pulsed compression coils. Figure 1



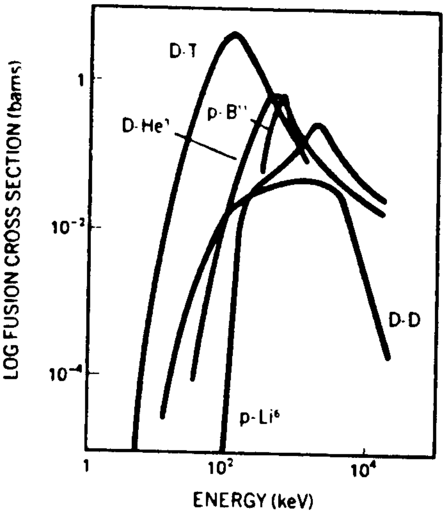
**The octopole has four levitated rings inside the plasma** to produce a rippled magnetic field concentrated at the surface, with a null at the center. A toroidal field can also be added to the poloidal field to reduce certain types of losses. Figure 2



**A SURMAC is a high-order multipole** producing more localized surface fields. The particular arrangement shown here has six rings, but the modular design of the SURMAC permits extension to any number of rings. Figure 3 losses are not as large as previously thought, so that a stable DT cusp reactor could be possible, the confinement would probably not be good enough for advanced fuels.

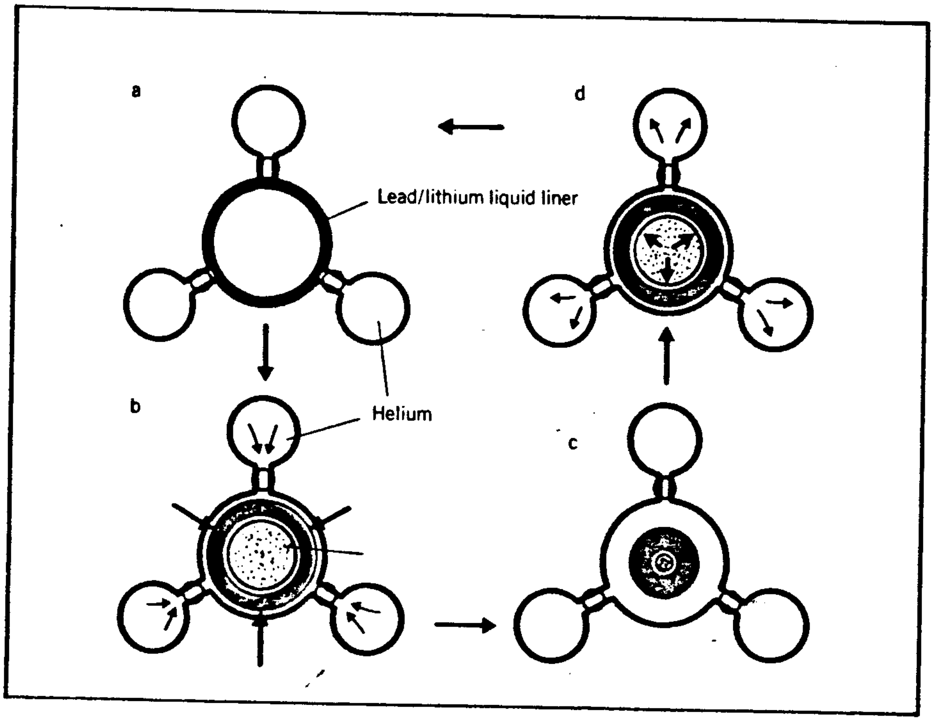
The multipole way is to close the lines of force by means of conductors inside the plasma. A four-ring system ("octopole") is shown in figure 2. The floating rings all carry current in the same direction and produce a poloidal field with a field null at the center. Return current flows in the wall or in another set of rings outside the plasma. The separatrices divide the volume into regions of "private flux," which encircle only one ring, and of "common flux", which encircle all the rings. The private-flux regions have absolute stability because the curvature is everywhere towards the plasma. The common-flux regions have field lines with alternating curvature. The plasma is stable up to the $\psi_c$ ("psi-critical") line, which has an average curvature of zero. Thus, the plasma fills the large region of low field and extends up to $\psi_c$. The region of low field can be made larger relative to the volume occupied by the surface field by increasing the number of conductors. A six-ring, modular device is shown in figure 3. Such high-order multipoles, or "surmacs" (SURface MAgnetic Confinement),[5] have lower synchrotron radiation and higher beta in the critical region near $\psi_c$, but they are more costly and leave less room under the separatrix for the conductor. The optimum number of rings is not yet known but is unlikely to exceed 4–6.

Years of experimentation on octopoles[6,7] have shown the effectiveness of "average-minimum-B" stabilization as well as elucidated the various mechanisms of cross-field transport in toroidal devices. Losses caused by unstable oscillations can be kept under control by the min-$\bar{B}$ effect, but plasma convection then becomes dominant at very long confinement times. Convective cells can arise from asymmetries in the boundaries or in the plasma production process. Even without these, computer simulations show that vortices can be generated thermally. The addition of a toroidal field component greatly reduces these losses.



**Fusion cross sections.** Advanced fuel cycles have lower fusion cross sections and require higher temperatures than D–T or D–D. However, they produce almost no neutrons and do not require the breeding of tritium. Figure 4

The encouraging results on confinement in multipoles have so far come from experiments at low density and temperature. More expensive experiments at higher density and temperature are clearly needed to test the behavior of multipoles closer to reactor conditions. For example, at higher densities ballooning modes are expected to occur. Although this name denotes instabilities localized in regions of bad curvature, the most easily excited modes actually sample both good and bad curvature regions, with only a slightly larger amplitude in the bad region. In the bridge region, between the ring and the wall, ideal hydromagnetics predicts a critical beta of about 1% for the onset of such modes. Since a beta of 3% has already been achieved in experiment, geometrical and finite Larmor-radius effects are apparently important stabilizing influences. The question is whether or not a beta value of the order of 20% can be achieved in the bridge region.



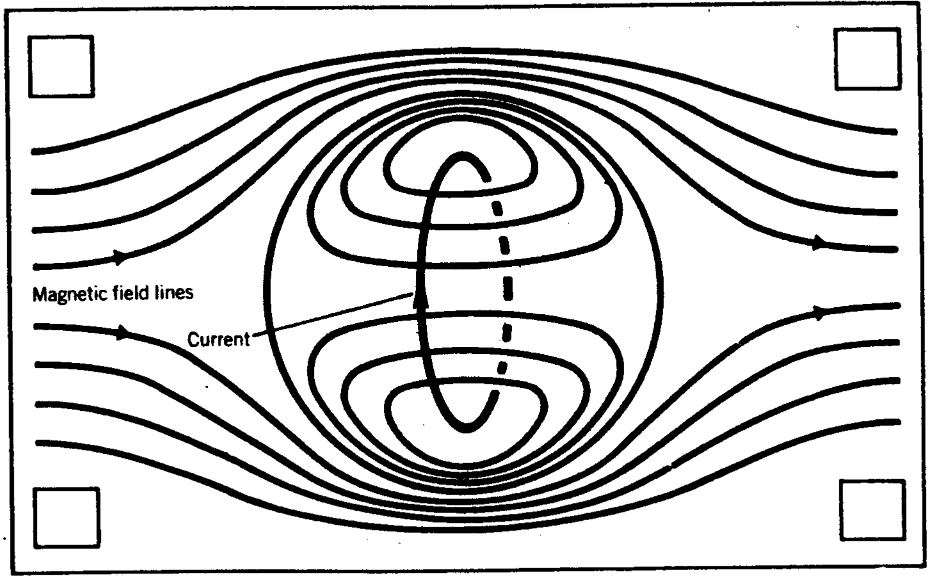
In the Linus concept a heavy liquid metal blanket or liner (Pb and Li) compresses the magnetic field to very high values. As the plasma burns, the liner absorbs the DT neutrons and the alpha particles deposit their energy in the plasma. The liquid liner is recaptured and reformed by reciprocating solid pistons after each pulse. Figure 5

For engineers, an obvious concern is the levitation and stabilization of the current-carrying rings inside the plasma. Both superconducting and normal floating rings have already been built and used in various laboratories. In an advanced-fuel reactor, the long confinement time would probably require dc operation with superconducting rings. As presently envisioned, the rings would be 50–100 cm in minor diameter and would consist of the following layers: Cu + NbTi superconductors immersed in liquid He, superinsulation, a heat-sink material that melts during operation, high-temperature insulation, refractory x-ray absorbing jacket and low-$Z$ first wall. There appears to be no reason why the temperature difference between the 10 K superconductor and the $10^9$ K plasma cannot be maintained for two days or so in a sealed system. Alternatively, one could consider rings that are continuously cooled by He flowing through small magnetically shielded pipes going through the plasma. The big question is whether or not these pipes would cause plasma losses by generating convective cells. A liquid-He cryostat might even be built right into the rings. This cryostat would be driven by the temperature gradient between the plasma side and the wall side of the rings, and the extra heat would be radiated away by a slightly higher surface temperature.

All bets are off, however, if the superconductors are exposed to a large neutron flux. Thus there is a fortunate symbiosis between advanced fuels and multipole-surmacs. Advanced fuel cycles produce very few neutrons, and internal ring devices can provide the good confinement and low synchrotron radiation required to burn the advanced fuels. In figure 4 are the fusion cross sections of several reactions compared to D-T and D-D. The most promising single reaction is

$$p + B^{11} \rightarrow 3\alpha + 8.7\ \text{MeV}$$

The cross section, unfortunately, is



**Field reversal** can be achieved by a ring of current injected or induced into an initially undirectional field. The current can be carried by energetic charged particles with large Larmor orbits, or it can be a plasma current of ions and electrons drifting around the axis. Figure 6

slightly too low for this reaction to produce net energy. Recent evidence suggests[8] that a chain reaction involving p-$Li^6$ could lead to plasma ignition: The three steps are

$$p + Li^6 \rightarrow He^3 + \alpha + 4MeV$$

$$He^3 + Li^6 \rightarrow 2\alpha + p^* + 16.8MeV$$

$$He^3 + He^3 \rightarrow \alpha + 2p^* + 12.9MeV$$

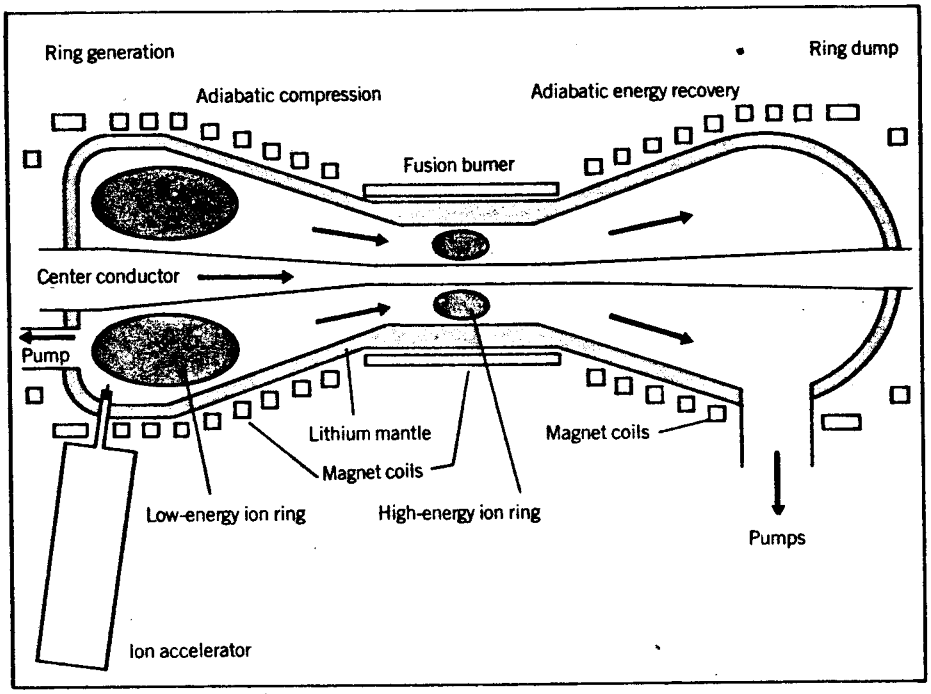
Burning of the $He^3$ provides a high-energy proton $p^*$ (5–11 MeV), which has a good chance of reacting with $Li^6$ as it slows down past the peak in the fusion cross section. Only a few neutrons are produced in parasitic reactions in this chain. If a few more neutrons are permitted by the floating-ring design, the burning of $He^3$ can be greatly expedited by the addition of a little deuterium to make use of the large D–$He^3$ cross section. Other low-$Z$ chains could well exist; a systematic search has not yet been made.

An advanced-fuel multipole-surmac reactor[9] would operate at temperatures of about 300 keV for ions and 150 keV for electrons, with an $n\tau$ product for electrons about the same as for tokamaks, and an ion $n\tau$ somewhat higher. Such a device would be a considerable step beyond the DT tokamak and would no doubt be a second- or third-generation fusion reactor. Yet the prospect of ultimately achieving a neutronless, tritiumless reactor would have a large impact on public acceptance of nuclear power. There would be no need to breed or contain tritium, and neutron activation of materials would be eliminated. Radiological safety would be almost absolute. Improving environmental impact in the area of waste heat is also possible: Since no neutron energy is produced, and the charged-particle energy is internally converted to plasma heat, the energy output of such a reactor would be in radiation—mostly x rays from electron bremsstrahlung. This high-grade form of energy could be converted to electricity in an efficient, high temperature thermal cycle.[10]

### High-density systems

Fusionists are forever bound by Lawson's dictum that $n\tau$ exceed a certain minimum value between $10^{14}$ and $10^{15}$ sec per $cm^3$, depending on the details. If plasma is so hard to confine, why not operate at large $n$ and small $\tau$? This philosophy is carried to an extreme in laser fusion, where the plasma is not confined at all, except by its own inertia. The high-density z-pinch[11] is a million times less extreme, but still a million times denser and quicker than a tokamak. In the z-pinch a large capacitor bank is discharged through a gas between two electrodes. A laser beam is used to seed a small channel, so that a 1.5 MA current flows within a diameter of 0.3 mm, leading to a self-field of $10^3$ T, sufficient to confine $n$ greater than $10^{20}$ $cm^{-3}$. No coils or auxiliary heating are required. Of course, z-pinches are notoriously unstable, and the question is whether or not the pulse can be finished before the instabilities grow. The shock-heated reactor[12] is another high-density scheme. Here a large current pulse is passed radially through a plasma between two coaxial conducting tubes. The plasma is shock-heated and compressed by an axially moving magnetic piston. Again, only a single power supply and no coils are needed. However, the field is too weak to confine the dense plasma, and the plasma pressure is held mechanically by the walls. The magnetic field is needed to reduce heat conduction to an acceptable level. A layer of dense, cold plasma forms near the walls, as in the solid endplug concept for linear systems. Wall containment is being investigated in a few places in Sweden and the USSR, but its effectiveness in confining reactor-grade plasma is still unknown. If this risky approach can be shown to work, it would certainly reduce the complexity of most magnetic systems.

The furthest developed of the high-density systems is the Linus,[13] or liquid liner, concept, which incorporates a



**The Ion Ring Compressor** achieves field reversal by the magnetic compression of a large ring current carried by nonrelativistic ions. In the scheme seen here, a pulse of 30-MeV deuterons is injected into a 0.14-T field to form a large, fat ring. Figure 7 number of novel features. This is a short linear system in which the magnetic coil is a liquid mixture of lead (for mass) and lithium (for conductivity), forming a hollow cylinder (figure 5). A preionized plasma with a weak magnetic field fills the cylinder (figure 5a). High pressure gas is introduced onto solid pistons around the liner, setting it into inward radial motion (part b of the figure). The plasma is compressed and heated, and the magnetic field is also trapped and compressed (part c) to 50–70 T. This field is higher than solid coils can withstand, and therefore operation at higher densities than conventional systems is possible. As the plasma burns, the DT neutrons are absorbed in the liner, and the alpha-particles deposit their energy in the plasma. The liner then turns around, pushed by the heated plasma (part c), and is recaptured in time for the next pulse. The liner is continuously pumped through systems that cool it and remove the tritium bred from the lithium. The Pb–Li blanket serves many functions and solves many engineering problems at the same time: it is a renewable first wall, an indestructible magnet coil, a neutron shield, a tritium-breeding medium, an energy-storage medium and the main coolant.

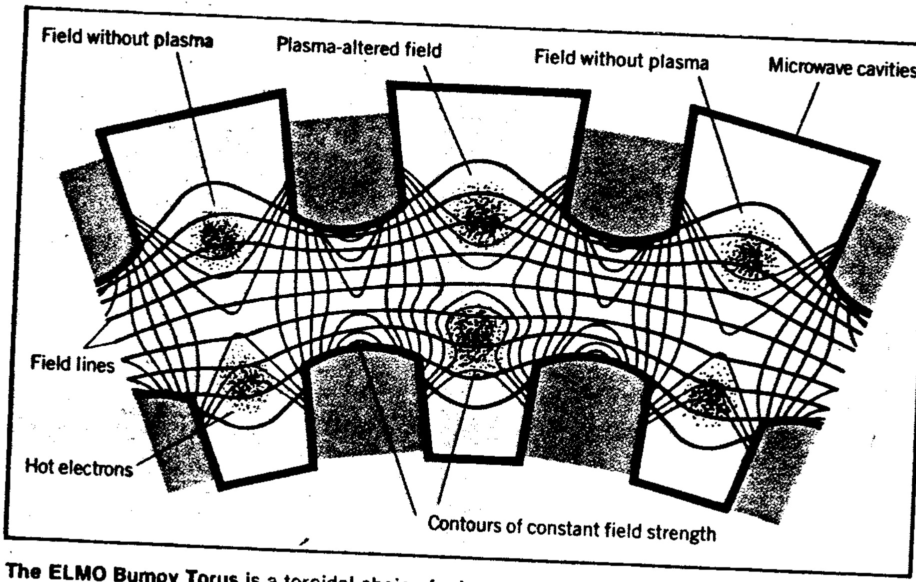
The Linus concept has both physics and engineering problems, and solutions have been proposed for all of them. Several of the most questionable features have been checked in successful experiments at the Naval Research Laboratory.[13] The feasibility of recapturing a liquid liner driven by high-pressure gas in repeated cycles has been demonstrated with water as the liquid. The inner surface of the liner is Rayleigh–Taylor unstable, but it can be stabilized by centrifugal force if the whole liner is rotated. The theoretical rotation speed required has been verified in experiments with a potassium–sodium mixture, as has the feasibility of creating large magnetic fields. The compressibility of the liner material limits the compression ratio and the field achievable, with approximately the same limit set by evaporation of the liner surface. To reduce the effects of evaporated impurities and to increase the conductivity, a layer of pure lithium at the inside surface is contemplated.

Perhaps the most difficult problem to overcome is that of an effective end-plugging scheme, so that the Linus need not be hundreds of meters long. The present idea is to produce a field-reversed magnetic configuration by injecting a helical relativistic electron beam initially. This induces a field-reversing plasma current, which persists long after the beam leaves. Such a current has been produced, but a closed-field configuration has not yet been achieved. Although it is a pulsed device, there is no reason why a Linus cannot work as smoothly as an automobile engine. The Linus offers a true alternative to the tokamak by treating the engineering problems in a new way.

## Particle rings

Hill's vortex in hydrodynamics has its analog in plasma physics in the Astron concept (figure 6) proposed long ago by the late Nicholas Christofilos. Here the streamlines are replaced by magnetic-field lines, initially those from a pair of magnetic mirror coils. A current of charged particles is injected to generate a field in the reversed direction on axis. This field turns the open system into a toroidal system with closed field lines; moreover, there is a field null at the position of the ring current, so that the plasma is trapped in an absolute magnetic well. In the original Astron, relativistic electrons from a conventional accelerator were injected, but sufficient current for field reversal could not be achieved by stacking successive pulses. Now the development of pulsed-diode generators has made the Astron a reality. At Cornell University,[14] a single pulse of electrons from a relatively small generator has already produced a reversed field 1.2 times the initial field, and the electron ring has been held stably.

For reactor purposes, however, electron rings have too much synchrotron radiation, and substitution of a nonrelativistic ion ring is proposed. Recent developments with diode generators operating with reverse polarity have made this a real possibility. A much larger number of ions would have to be injected to make up for their slower speed. The trick is to compress the ion ring by increasing the background magnetic field after the ring is formed. It can easily be seen from energy and momentum conservation that the amount of field reversal is increased this way. Electron rings do not have this benefit because they would be relativistic. In the Ion Ring Compressor scheme[14] (figure 7), a pulse of 30-MeV deuterons is injected into an 0.14 T field to form a large, fat ring—the most stable shape. If needed, an axial conductor can add a toroidal field. The ring is then compressed and transferred to the burn region, creating and entraining plasma along the way. Field reversal is achieved only in the compressed state. After the burn, the ring would be transferred to a dump chamber, and part of its energy recovered electromagnetically. In electron analog experiments at Cornell, the processes of ring compression and transport and the effects of toroidal and quadrupole fields have all been checked. Although the detailed reactor studies necessary to show a clear engineering advantage over the tokamak have not yet been done, progress on the physics of ion ring devices so far has been impressive, and no insuperable obstacles have been found.



**The ELMO Bumpy Torus** is a toroidal chain of microwave cavities, which produce trapped rings of hot electrons by cyclotron resonance. Side sections show magnetic field without plasma; center cavity is plasma-altered configuration. The electron rings form a magnetic well for the plasma, as shown by the constant $\bar{B}$ contours in the center section. Figure 8

## Mirror–torus hybrids

Some alternative concepts are an attempt to combine the best features of open and closed systems. The Tormac[15] and the ELMO Bumpy Torus (EBT) are devices that have already had a long history of experimentation. The Tormac has two distinct field regions separated by diamagnetic currents in a thin sheath. The interior region has a weak toroidal field, and the field lines do not leave this region. The exterior field is entirely poloidal and is in the shape of a double circular cusp. To reach this region of open field lines, plasma must first diffuse across the toroidal field. Once they are in the sheath, particles are mirror-confined by the large field in the cusps. Taken together, the two fields form an absolute magnetic well, so stability at high beta is possible. Further advantages are possible dc operation, natural divertors for removal of impurities and injection of fast ions, and reduced synchrotron radiation. Two major problems have not yet been solved: stability of the collisionless sheath, and maintaining toroidal equilibrium and stability in the interior.

A simple magnetic mirror (two coils, with the magnetic field bulging out in between) loses plasma too rapidly out of the ends. An obvious solution would be to capture the escaping plasma in another mirror section. The EBT[16] (figure 8) is basically a chain of magnetic-mirror sections bent around into a torus. Although the toroidal curvature is small, it cannot be neglected. Toroidal equilibrium requires that the particles circulate around the minor axis. In a tokamak this is accomplished by twisting the lines of force. In the EBT, the particles drift in the azimuthal direction because of the large radial gradient in field strength.

Instabilities driven by the centrifugal force of particles moving along bent field lines are another problem. In the tokamak, these are stabilized by shear in the magnetic field; in the EBT, the minimum-B (magnetic well) effect is used. The bumpy torus sections are in reality microwave cavities; intense radiation at the electron cyclotron frequency not only heats the plasma but also creates a ring of energetic (200 keV) electrons trapped in each mirror section. The diamagnetic current of these hot electrons is not sufficient to cause field reversal, but it does depress the field enough to form a local magnetic well. An operating regime in which both the plasma and the hot electron ring are stable has been seen in experiments at Oak Ridge. Since no toroidal current needs to be induced in the plasma, it can be maintained in steady state; in fact, a most impressive feature of the experiments is that they were done dc, with continuous wave microwave generators, and with the plasma in equilibrium with impurities from the walls. As a reactor, the EBT would be like a dc tokamak with large aspect ratio—and hence good accessibility from all sides. The major remaining physics question is whether or not the stability of the plasma and the electron annulus can be maintained at higher densities and temperatures. The big engineering question is the reliability of the 120-GHz, 200-kW cw gyrotrons being developed for this machine.

### Reversed-field systems

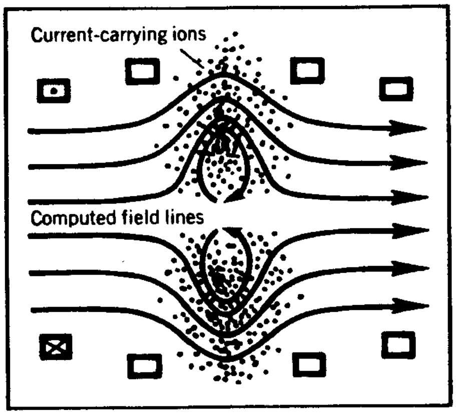
Several quite different devices have been grouped into the category of reversed-field systems. In the field-reversed mirror[17] (figure 9), ionization of an intense beam of neutral atoms forms a current-carrying layer of energetic ions. In mirror experiments at Livermore, California, neutral beams used for ion heating have come close to injecting enough current to cancel the initial field. In the reversed-field theta pinch, a fast pulse of azimuthal current is induced in a preionized plasma imbedded in a uniform axial field. The rapidly rising magnetic field compresses and heats the plasma and the current layer reverses the field, forming a toroidal configuration with closed field lines.

Although these two concepts have a magnetic topology identical to that of the Astron (figure 6), a great difference exists in the physics. If field reversal is achieved by a ring of axis-encircling ions or electrons, the plasma is stable as long as the ring is stable, since the plasma sits in a magnetic well dug by the ring. The ring acts like one of the solid rings of a multipole, except that it can coexist with the plasma. Stability of a particle ring depends on beam–plasma interactions, particle resonances with external fields or plasma modes, and so on; these considerations lead to rings shaped like a bicycle tire.

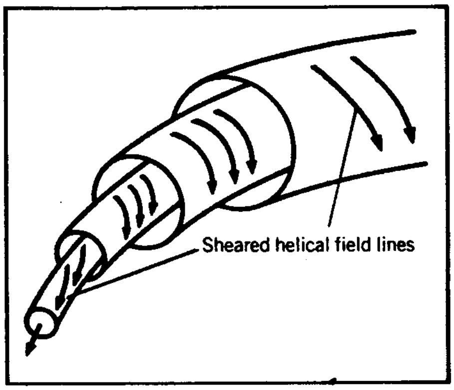
If, on the other hand, field reversal is achieved by a plasma current carried by electrons with small Larmor radius drifting around the axis, no minimum-B stabilization effect can be expected. A plasma cannot be stabilized by a magnetic well dug by itself; after all, any plasma has a magnetic well dug by its own diamagnetic current. The linear theta pinch, then, is not stable—except in experiment! The reason for the observed stability of reversed-field theta pinches is not yet known; image currents on the boundaries and the formation of magnetic islands are among the possible mechanisms. Because there is no ring of particles to stabilize, the best shape is not a fat torus, but a long and thin one—for the same reason that tokamaks and belt-pinches perform better when they are elongated. (The stability limit is higher, because the destabilizing force is related to the toroidal curvature, not the length.)

In a field-reversed mirror, the fast ions do not encircle the axis but still have large orbits—typically a quarter to a half of the plasma size. Stability in this intermediate case is difficult to analyze; the ion trajectories must be followed on a computer. If field reversal can be achieved, the problem of end losses in a mirror would be solved; and we could then achieve power balance in very small reactor modules producing only tens of megawatts each. Several other obstacles, however, must be overcome. One is that of stability during the time the current layer is being formed. It is customary to add a quadrupole field to a mirror for minimum-B stabilization, but in a field-reversed mirror this stray field would cause the lines of force to wander out of the machine. It may be necessary to add shear with an axial conductor. Current cancellation is also a problem:—frictional drag can cause the electrons to drift along with the ions, neutralizing their current. (A large radial electric field must develop to drive the electron gyration centers azimuthally.) A possible remedy for this is to add a high-$Z$ impurity. Electrons can then cancel either charge or current, but not both; charge neutrality will always win out.

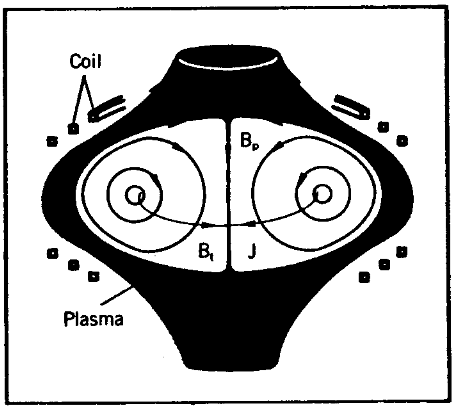
The reversed-field toroidal z-pinch (figure 10) has a weaker toroidal field than a tokamak, and a much larger plasma



**The field-reversed mirror** is topologically similar to a particle ring system (figure 6), but the current-carrying particles do not encircle the axis. Once field reversal is achieved in an open system, it becomes a toroidal system. Figure 9



**A reversed-field z-pinch** has a force-free plasma current large enough to reverse the direction of the external toroidal field. Note that toroidal component of field has changed direction more than 90°. Figure 10



**The Spheromak** is the ultimate reversed-field configuration. It combines the best features of toroidal and mirror confinement, and the necessary field shape is produced by currents in the plasma itself. Figure 11 current. This current, which flows along the sheared, helical field lines, not only supplies the poloidal field component, as in the tokamak, but also generates enough toroidal component to reverse the original toroidal field. The fact that the Hamiltonian does not depend on the azimuthal angle $\phi$ in an axisymmetric system leads directly to the result that classical diffusion depends only on the strength of the poloidal field. By increasing the poloidal field and decreasing the toroidal field, the tokamak's use of magnetic fields might be improved. Unfortunately, tokamak stability is lost, despite shear stabilization, because the plasma current is far above the Kruskal–Shafranov limit. If however, wall stabilization is assumed, a unique distribution of currents leads to a minimum of the total energy; this is the configuration of maximum inductance, as pointed out by J. B. Taylor.[18] Indeed, examination of data from the old Zeta machine at Culham, UK, reveals a period of quiescence in agreement with the predictions of Taylor's theory. This leads to the hope that a stable z-pinch can be set up after an initial period of turbulence. If so, the device would not suffer from the small aspect ratio of the tokamak or the need for auxiliary heating. However, the prospect of maintaining a highly conducting wall near the plasma in a reactor is not a pleasant one.

Once field reversal is achieved in a mirror, the distinction between a torus and a mirror vanishes. The ultimate in a field-reversed configuration is the spheromak[19] (figure 11). Here all the needed toroidal and poloidal currents flow in the plasma itself. The magnetic fields and currents along them are arranged in a force-free configuration. Of course, there must be an external field to keep the whole plasma blob from expanding. Preliminary calculations show that such an object can be stable, provided it has the oblate shape shown. The spheromak is like a tokamak with strip divertors, except that the D-coil current is replaced by a plasma current. Compared with a field-reversed mirror, the spheromak is identical except for the addition of a plasma current along the axis, as can be seen by rotating the diagram 90°.

How can one set up such a system of fields and currents in an isolated volume of plasma? There are, *mirabile dictu*, proposals for doing this with plasma guns, and experiments are in progress. Whether or not these will ever succeed on a reactor scale is highly conjectural, but one can look forward to the day, 100 years from now, when we will have mastered the techniques of plasma production, heating and confinement, and the plasma will become simple again. Remember how complicated the vacuum tube used to be?

* * *

*This article is based on a talk given at Colorado Springs, 3 November 1978, to the American Physical Society Division of Plasma Physics.*

*The ingenious ideas described here are the work of many clever people. Space limitations do not permit giving due credit to all of them; I have therefore uniformly omitted all names except in the following list of references.*

## References

1. L. C. Steinhauer, G. C. Vlases, Nuclear Fusion **19**, to be published in 1979.
2. V. Bailey, J. Benford, R. Cooper, D. Dakin, B. Ecker, O. Lopez, S. Putnam, T. S. T. Young, *Proceedings of the 2nd Int'l Topical Conf. on High Power Electron and Ion Beam Research and Technology* (Laboratory of Plasma Studies, Cornell University, Ithaca, N. Y., 1978).
3. E. Ott, R. N. Sudan, Appl. Phys. Lett. **29**, 5 (1976).
4. N. Hershkowitz, J. R. Smith, H. Kozima, Phys. Fluids **22**, 122 (1979).
5. A. Y. Wong, Y. Nakamura, B. H. Quon, J. M. Dawson, Phys. Rev. Lett. **35**, 1156 (1975).
6. J. R. Drake, D. W. Kerst, G. A. Navratil, R. S. Post, *Plasma Physics and Controlled Nuclear Fusion Research 1976, II*, page 333, IAEA, Vienna (1977); Phys. Fluids **20**, 148, page 156 (1977).
7. T. Tamano, Y. Hamada, C. Moeller, T. Ohkawa, R. Prater, *Plasma Physics and Controlled Nuclear Fusion Research 1974, II*, page 97, IAEA, Vienna, (1975).
8. R. W. Conn, G. Shuy, Fusion Technology Program Report FDM-262, Revised, Univ. of Wisconsin, Madison, 1979.
9. J. M. Dawson, EPRI Report ER-429-SR, Part C, Electric Power Research Institute, Palo Alto CA 94304, May 1977.
10. R. T. Taussig, EPRI Report ER-544 Electric Power Research Institute, Palo Alto, CA 94304, April 1977.
11. C. W. Hartman, G. Carlson, M. Hoffman, R. Werner, Nuclear Fusion **17**, 909 (1977).
12. R. A. Gross, Nuclear Fusion **15**, 729 (1975).
13. P. J. Turchi, D. L. Book, R. L. Burton, A. L. Cooper, J. of Magnetism and Magnetic Materials, to be published (1979).
14. H. H. Fleischmann, T. Kammash, Nuclear Fusion **15**, 1143 (1975).
15. M. A. Levine et al., *Plasma Physics and Controlled Nuclear Fusion Research 1978*, paper CN-37-E4 IAEA, Vienna, 1979.
16. R. A. Dandl, H. O. Eason, P. H. Edmonds, A. C. England, G. E. Guest, C. L. Hedrick, J. T. Hogan, J. C. Sprott, *Plasma Physics and Controlled Nuclear Fusion Research 1971, II*, page 607, IAEA, Vienna, 1972.
17. B. McNamara, D. V. Anderson, J. K. Boyd, J. A. Byers, R. Cohen, T. A. Cutler, L. S. Hall, R. F. Post, M. E. Rensink, *Plasma Physics and Controlled Nuclear Fusion Research 1976, III*, page 161, IAEA, Vienna, 1977.
18. J. B. Taylor, Phys. Rev. Lett. **33**, 1139 (1974).
19. M. N. Bussac, H. P. Furth, M. Okabayashi, M. N. Rosenbluth, A. M. Todd, *Plasma Physics and Controlled Nuclear Fusion Research 1978*, Paper CN-37-X1 IAEA, Vienna, 1979. ☐