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by J. Reece Roth
Lewis Research Center
Cleveland, Ohio 44135

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Dr. J. Reece Roth
NASA Lewis Research Center
Cleveland, Ohio

ABSTRACT

This paper discusses the potential applications of fusion reactors, the desirable characteristics of reactors intended for various applications, and the limitations of the tokamak concept. The plasma physics literature has been surveyed, and 20 distinct alternative confinement concepts have been identified. The principles and characteristics of these concepts are described, and selected literature is cited for each. Because these concepts are in an early stage of investigation, all of their advantages and limitations are not well defined. They may offer one or more advantages over the tokamak and provide an alternative to it after further development. Eighteen of these concepts have been reduced to practice in the form of an operating experimental device.

INTRODUCTION

When the energetic ions which form the fuel of a fusion reactor are confined in a strong uniform magnetic field, their trajectories are helices. The trajectories projected along a magnetic field line are circles with a characteristic radius of gyration. The particles are trapped on the magnetic field lines if they suffer no collisions. When collisions occur, the particles perform a slow random walk across the magnetic field toward the walls of the containment vessel, with a step size equal to the particle gyroradius. This transport process is called classical diffusion. Fusion reactor design studies have shown that if plasma diffuses across a magnetic field no faster than the classical rate, a net power producing fusion reactor is feasible.

Progress made in the magnetic containment of plasmas in toroidal devices is indicated on figure 1, which is taken from an early report by Eastlund and Gough (ref. 1). The containment time appropriate to classical diffusion is indicated on the ordinate, as is the containment time required for an economically attractive fusion reactor (indicated by the heavy black bar). When fusion research started in 1952, the plasmas were immediately lost to the wall. After a few years of research, the confinement time reached the so-called "anomalous" or Bohm value. This is well below the classical value, and is too low for economically attractive fusion power plants to be feasible The confinement times remained constant at the Bohm value for nearly ten years. It was not until 1965 that the Russians, with their tokamak device, first reported confinement times significantly greater than the Bohm value. After this, progress in toroidal plasma confinement was relatively rapid. By 1970, several experiments reached and exceeded the value required for an economically attractive fusion reactor. This breakthrough in plasma confinement is responsible for the current phase of optimism in controlled fusion research.

Plasma confinement time is not the only measure of progress in fusion research. On figure 2 is shown the Lawson diagram, which plots ion energy on the ordinate and the product of density and containment time on the abscissa. The region appropriate to net power producing fusion reactors is located within the curve in the upper right. The solid dots refer to tokamak experiments currently in operation (see, for example, ref. 2). There has been steady progress toward the fusion reactor regime, with the Alcator experiment at MIT currently in the lead.

The success of the tokamak reactor in achieving high ion kinetic temperatures, confinement times, and number densities has made it the concept of choice in all major industrial countries which are pursuing fusion research. The open circles on figure 2 show the anticipated operating parameters of several large tokamak experiments which are under construction. It is hoped that these experiments will approximately break even, i.e., produce as much power as is required to maintain the plasma (ref. 3). It is the current consensus that the first demonstration fusion power plants will be DT tokamak devices (refs. 3 and 4).

Twenty distinct plasma confinement concepts will be described, each of which may be an alternative to the tokamak fusion reactor. A limited number of references are cited for each concept, in which further information may be found. Excluded from the scope of this survey are inertial confinement schemes based on irradiating fuel pellets with lasers or relativistic particle beams; pinches; minor variations of the tokamak concept itself; and devices which cannot feasibly be used as a fusion reactor, including those which have conductors entirely surrounded by plasma.

USES AND DESIRABLE CHARACTERISTICS OF FUSION REACTORS

The programs to develop fusion reactors in major industrialized countries all assume that such reactors will be used only by the electric utilities. However, fusion reactors could have many other applications. Some potential applications of fusion reactors are listed in Table I, along with the primary requirements for each. A major application is large stationary power plants, which includes power generation for electric utilities; steam generation and space heating;

nuclear steel making, that is, the use of fusion rather than chemical energy to produce steel; chemical processing; water purification; and conversion of fertile to fissile material, that is, the breeding of fuel to be used in conventional nuclear power plants. Fusion power plants for such applications should have over-all costs that are competitive with other primary fuels. They must be reliable, and they must have minimal environmental intrusion.

TABLE I

APPLICATIONS OF FUSION POWER PLANTS

APPLICATION	REQUIREMENTS
1. Electric Utilities Steam Generation and Space Heating Nuclear Steelmaking Chemical Processing Water Purification Conversion of Fertile to Fissile Material	A. Competitive Capital Cost B. Reliability C. Minimum Environmental Intrusion
2. Space Power and Propulsion	A. Minimum Total Mass for Given Power Output B. Reliability and Ease of Repair C. Energy Release in Charged Particles
3. Military	A. Mobility B. Reliability C. Invulnerability

A second major area of application is space power and propulsion. This application has been discussed in ref. 5, and its principal requirements are a minimum total mass for a given power output; reliability and ease of repair; and a fuel cycle which releases most of its energy in charged particles, which can be used for the exhaust jet of a rocket. A third major use is military applications, which require mobility, reliability, and invulnerability.

It is an interesting sidelight on fusion research that the tokamak programs mounted by all major industrial countries are attempting to reverse the normal course of development of a new energy source. Most power sources and energy conversion devices now in common use were developed first for mobile applications. Only after they were light, cheap, and reliable enough to be used in mobile applications were they applied to stationary power plants and other industrial applications. The gasoline engine, the diesel engine, the nuclear power plant, steam turbines, and jet engines were all developed for mobile applications before they were widely used in stationary power plants. Even steam engines were not competitive with water power and did not receive widespread industrial use until their technology was refined by use on steamboats and railroads. In fusion research, the main line of technological development is proceeding directly toward stationary power plants without being refined by the discipline imposed by mobile applications.

In order to provide criteria by which fusion reactor concepts can be judged, it is useful to specify desirable characteristics which a fusion reactor should have. Such a list is given in Table II. Not all of these characteristics are necessarily desiarble for all possible applications of fusion reactors, but they do imply increased attractiveness of fusion power for at least one of the areas of application.

TABLE II

Desirable Characteristics of a Fusion Reactor

A. Steady-State Operation
B. High Beta
C. Self-Sustaining Fusion Reaction
D. Advanced Fuel Cycles Possible
E. Direct Conversion to Electrical Power
F. Small Size and Power Output
G. No Neutrons or Activation of Structure
H. Environmentally Safe
I. High Capital and Resource Productivity

In the first place, a fusion reactor should operate in the steady state. Power interruptions associated with cyclic operation are awkward for the utilities if the interruptions are comparable with the thermal time constant of the plant. Many of the pulsed or inertially confined concepts suffer a disadvantage because it is more difficult to extract energy with high efficiency when it is released in a pulsed manner. Pulsed fusion reactors also suffer the disadvantage that they must be designed to bear the maximum thermal and mechanical stresses, rather than designing to the average values appropriate to a steady-state reactor.

It is generally believed that the magnet cost for a fusion reactor will be minimized if the reactor operates at a high value of beta, the ratio of plasma to magnetic energy density. High values of beta imply smaller reactor sizes, lower capital investment in the magnetic field, containment structure, and blanket, and less synchrotron radiation for a favorable energy balance.

It is desirable that a fusion reactor be capable of a completely or nearly self-sustaining fusion reaction in which the energy released in charged particles is used to heat the incoming fuel in the plasma itself, rather than heating the fuel with large or expensive external equipment prior to injection.

A fusion reactor should be capable of operating with advanced fuel cycles (fuel cycles other than the DT reaction) since such fuel cycles release more of their energy in the form of charged particles. Some advanced fuel cycles (the proton-boron-11, for example) are capable of operating without producing energetic neutrons. The DD reaction has cross-sections second highest only to the DT reaction and uses a plentiful fuel which is available without breeding.

Advanced fuel cycle reactors which release their energy in the form of charged particles should be capable of operating in such a way that the energetic charged particles, which would otherwise diffuse to the walls of the containment vessel, can be scavenged and converted to electrical power by one of several direct conversion schemes.

For military or space applications, it would be desirable if a self-sustaining fusion reactor were of small enough size and power output that it could operate as a mobile power source.

Any fusion reactor must be environmentally safe, and one means of minimizing possible radiation hazards is to use one of the advanced fuel cycles which either do not generate neutrons or minimize the neutron generation and/or activation of the reactor structure.

LIMITATIONS OF THE TOKAMAK CONCEPT

Fairly detailed design studies of the tokamak concept, such as those summarized by Davis and Kulcinski (ref. 3) have indicated a capital cost and a cost of electricity at least equal to that of fission and breeder reactors. Such findings have led some representatives of the electrical power industry to question the viability of the tokamak concept as an energy source for the electrical utilities, regardless of its value in demonstrating fusion feasibility (refs. 6 and 7). It is therefore of interest to examine the limitations of tokamaks to provide a basis for comparison with other concepts.

When measured against the criteria discussed in Table II, the present tokamak fusion reactor conceptual designs (refs. 4, 6, and 7) are seen to have limitations in several areas. These are listed in Table III.

TABLE III

LIMITATIONS OF THE PRESENT TOKAMAK CONCEPTUAL DESIGNS

A. Must Operate in Cyclic Manner
B. Low Beta Required for Stability
C. Advanced Fuel Cycles Appear Infeasible
D. Fusion Reactions May Not be Self-Sustaining
E. Capital and Resource Productivity No Better Than Fission Reactors
F. Massive, Stationary Power Plant

The tokamak concept cannot operate in the steady state, because the plasma currents in the toroidal direction serve a double function; they not only create and heat the plasma by ohmic heating, but these currents also generate the poloidal magnetic field which is required to confine the plasma. When this plasma current decays below a certain threshold, confinement is lost and the plasma must be restarted in a cyclic manner. Various design studies estimate that a tokamak fusion reactor might burn for a few minutes to one hour, and that one or a few minutes might be required to purge the confinement volume and restart the plasma (ref. 3). If the down time required for purging and restart is comparable to the steam plant time constant, cyclic power production could be very undesirable for utility applications.

At present, it appears that stability considerations will limit tokamak fusion reactors to a low value of beta, on the order of 5%. Because of these low values of beta, it appears difficult to operate tokamak reactors with advanced fuel cycles. These require higher kinetic temperatures, and a low value of beta would require much larger volumes or stronger magnetic fields to generate the same total power output. If the ion and electron temperatures of the plasma are equal, the magnetic field required to confine plasmas using advanced fuels at low beta would imply amounts of synchrotron radiation sufficient to quench the reaction. The limitation to low beta may restrict tokamak reactors to the DT reaction. The current state of understanding is probably not sufficiently advanced to state whether or not a tokamak DT reactor would be self-sustaining as a result of the slowing down of alpha particles in the plasma; if significant amounts of external heating of the fuel were necessary, as by energetic neutral injection, this would represent a substantial burden of capital equipment necessary to recycle the power.

SURVEY OF ALTERNATIVE APPROACHES TO PLASMA CONFINEMENT

The devices discussed below each appear to improve upon one or more of the limitations of the present tokamak fusion reactor designs.

Some of them, in their current versions, also have drawbacks as bad or worse than the tokamak concept. Because these concepts are in an early stage of investigation, all of their limitations and advantages are not well defined. An attempt has none the less been made to summarize the advantages and limitations of each concept in Table IV at the end of the report.

TOKAMAK-LIKE DEVICES

Tormac

The Tormac confinement concept has been developed by M. A. Levine and his colleagues (refs. 8-11). The current-carrying conductors of the Tormac concept are shown in figure 3. A current flows through the plasma in the toroidal direction. The arrangement of the magnetic field differs from that of the tokamak in that the plasma is confined in a toroidal cusp configuration with two annular cusps or vertices facing outward away from the major axis of the torus. The principal motivation for this geometry is to achieve a higher degree of macroscopic plasma stability than is possible in the tokamak by using the cusp geometry, in which the magnetic field lines tend to restrain gross motions of the plasma. In principle, the Tormac should be capable of confining plasmas at values of beta approaching unity, rather than the low values which are necessary for stability in the tokamak.

There is some recent experimental evidence that plasma is stably confined in the Tormac, and at higher values of beta than would be possible in an equivalent tokamak. A photograph of the Tormac plasma is shown in figure 4. In this particular version of the Tormac, the magnetic field is generated by thin wires connected to capacitor banks so that the entire plasma volume is visible. The plasma in this experiment contains strong toroidal currents which help to confine the plasma. If these cannot be eliminated, the Tormac is basically a cyclic plasma containment concept.

Topolotron

The Topolotron concept has been developed by R. W. Bass, J. H. Gardner, et al. (refs. 12-14) at Brigham Young University in Provo, Utah. The basic Topolotron configuration is shown in figure 5, and arose from highly abstract considerations relating to the topological properties of toroidal magnetic field configurations. The Topolotron exhibits a property known as topological stability, which may also imply improved stability and confinement of a high beta toroidal plasma. A comparison of the current-carrying conductors of the Tormac and the Topolotron in figures 3 and 5 shows that they are basically an inside-out version of each other, with the two annular cusp-like vertices pointing radially inward in the Topolotron and outward in the Tormac. In the Topolotron, the currents flowing in the plasma have a poloidal component, like the theta pinch, while they flow only in the toroidal direction in the Tormac.

The Topolotron has a further interesting property illustrated in figure 6. The magnetic field lines on the plasma surface are indicated by the arrows in this figure, and they tend to reach limit cycles at the two cusp-like points on the inner circumference of the plasma volume. Whether this limit cycle behavior also implies an undesirable piling up of particles at the two cusp points remains to be seen. A projection of the poloidal component of the magnetic field is shown in figure 7. On figure 8 is shown a photograph of the Topolotron apparatus in a partially assembled state. If the Topolotron concepts could be scaled up to a fusion reactor, its advantages and disadvantages would be similar to those of the Tormac.

THE EXTRAP CONCEPT

The Extrap concept has been proposed by Bo Lehnert of the Royal Institute of Technology in Stockholm (refs. 15 and 16), and is illustrated by the diagram in figure 9. This axisymmetric toroidal device has similarities to the Tormac and Topolotron. The poloidal magnetic field required for confinement is provided by four coils that encircle the major axis of the torus, all the currents of which flow in the same toroidal direction. These four coils are external to the plasma, and in an operating reactor could be shielded from it. It is also necessary to have a toroidal current flowing in the plasma, much like the tokamak concept, in order to provide stability and confinement. The combination of the currents in the four external coils and the oppositely directed toroidal current in the plasma itself confine the plasma within the magnetic field lines shown in figure 9. A small version of this device has been tested (refs. 15 and 16) with encouraging results. Although this is basically a pulsed concept because of the induced currents flowing within the plasmas, it has several advantages over the tokamak, including a simpler magnetic field geometry which could allow easier remote disassembly.

STELLARATOR-LIKE DEVICES

The Classical Stellarator

The Stellarator concept was originated in the U.S. at Princeton in 1952 (ref. 17), but has fallen into relative neglect in the United States since 1969. In order to appreciate the merits of the stellarator concept, it is helpful to understand why a simple toroidal magnetic field is not adequate to confine a plasma. In figure 10 is shown a simple torus with magnetic field windings around the toroidal volume. Because of the effect of toroidal curvature, the current-carrying conductors are more closely bunched on the inside circumference of the windings than they are on the outside. This leads to a stronger magnetic field along the inside radius of the plasma than along the outside. The resulting gradient of magnetic field along the major radius of the torus causes particles of opposite sign to drift to the top or bottom of the torus. This charge separation leads to electric fields which cause the toroidal plasma to drift to the walls. In order to overcome this bunching of the magnetic field lines along the inside circumference, one can twist the torus into a figure eight pattern like that shown in figure 11. This will assure that all of the magnetic field lines have approximately equal length, and the effects of the particle drifts will cancel as the particles traverse a complete circuit of the torus. This figure eight geometry is awkward to implement in an actual experiment, so the same effect is achieved by a combination of current-carrying windings illustrated on figure 12. The tightly wound helix represents coils which produce the toroidal magnetic field.

Inside the toroidal field coils are loosely wound helical windings. The currents in adjacent pairs of the helical windings flow in opposite directions and the net effect is a magnetic field in which the field lines rotate about the minor axis of the confinement volume by an amount proportional to the radius. The rotation of the magnetic field lines about the minor axis of the confinement volume is called rotational transform, and the differing amounts of rotational transform as one moves along the radius is referred to as magnetic shear.

A plot of the magnetic field strength contours and a particle drift surface are shown in figure 13 for the Proto-Cleo device at the University of Wisconsin (ref. 18). On figure 14 is shown an experimental determination of the drift surfaces of such a stellarator. To obtain this picture, a small electron gun was placed at various radii in a stellarator geometry, and multiple exposures of the electron impacts on a fluorescent screen were made as the electron gun was moved along equal increments in radius.

Figure 15 is a photograph of one of the early stellarators, which is about 1 meter by 2 meters long in a racetrack configuration. Stellarator research in the U.S. has been summarized by Young (ref. 19). Outside the U.S., there currently are active stellarator research programs in Russia, West Germany (ref. 20), England (refs. 21 and 22), France, and Japan. Figure 16 is a photograph of the West German Wendelstein VII stellarator, which is symmetric without the straight sections used in the early Princeton experiments. The only stellarator experiment currently active in the United States is the Proto-Cleo experiment at the University of Wisconsin which is shown in figure 17 (ref. 18).

The stellarator geometry has the important advantage over the tokamak that all the currents which confine the plasma are external to it. For this reason, the stellarator can be operated in the steady state and does not have to be operated in a cyclic manner to re-establish the toroidal currents. In addition, the stellarator may be capable of operating at somewhat higher values of beta than the tokamak.

Torsatron

The torsatron is a close relative of the stellarator geometry, in which rotational transform and shear of the magnetic field lines are achieved with a much simpler conductor geometry. The torsatron concept is under investigation in England (ref. 23), in Russia (ref. 24), and in the United States (ref. 25). A simple $\ell = 1$ torsatron with a single helical winding (ref. 24) is shown in figure 18. The $\ell = 3$ torsatron conductor geometry is illustrated in figure 19 which is a photograph of the torsatron windings in use at the Culham Laboratory (ref. 23). There are three conductors wound around the toroidal volume, each of which carries current in the same direction. These helical windings serve the same function as the combination of toroidal and helical windings in a stellarator, with the poloidal component of the current generating the toroidal magnetic field, and the toroidal component of the current generating the poloidal magnetic field. This particular geometry has a sector periodicity of 30 degrees. The drift surfaces in 5 degree increments along one of these sectors are shown in figure 20. The windings shown in figure 19 are contained in a large vacuum tank, a sketch of which is shown in figure 21. A photograph of the torsatron plasma taken through one of the top viewports of this vacuum tank is shown in figure 22.

An examination of figures 18, 19, and 22 makes obvious the basic simplicity of the torsatron magnetic field windings, which is very significant from an engineering point of view. The torsatron has a further interesting property which, as it happens, is not exemplified by these particular experiments. In figure 19 one can see the mechanical supports which bear the forces between the current-carrying conductors. With the torsatron geometry it is possible in principle to design the helical conductors in such a way that they are a force-free configuration, that is, no net mechanical forces will act between the individual conductors. The only forces would act along the conductors and such forces can be dealt with by making the conductors sufficiently strong in tension or compression. This represents a potential saving in structural material, and also can be made into a fail-safe design in which one does not have to design for unbalanced magnetic forces. The only forces which act on the conductors are gravitational forces, tensional forces along the axis of the conductor, and forces which arise from a finite plasma beta relative to the force-free vacuum field configuration.

The "Twisted-Coil" Stellarator

A serious objection to the classical stellarator is that it has a complicated set of windings, with helical conductors wound inside the bores of the toroidal field coils. Such a configuration is difficult to assemble. It is even more difficult to disassemble in a fusion reactor context where remote handling methods will be required. The Torsatron produces stellarator-like drift surfaces with helical conductors wound around the major circumference of the confinement volume. An alternative is the "twisted-coil" stellarator of Rehker and Wobig (ref. 26), the essence of which is shown in figures 23 and 24 for the $\ell = 2$ stellarator and in figures 25 and 26 for the $\ell = 3$ stellarator. The resulting drift surfaces are equivalent in their confinement and stability properties to those produced by the classical stellarator or the torsatron. The coil assembly has the important engineering advantage that the individual coils can be removed as modules from the toroidal array without having to disconnect a helical winding (as in a classical stellarator), or having to disconnect a helical coil which entirely encircles the major axis of the torus (as in the torsatron). The individual coils are shown in plan, side, and elevation views in figures 23 and 25. In the toroidal array, the individual coils are rotated in angle with respect to each other as one moves around the major circumference of the torus, to produce the rotational transform characteristic of the basic stellarator concept. This rotation of the coils is illustrated in figures 24 and 26. The twisted-coil stellarator concept has not yet been implemented in any working device.

The conductor configuration of the classical stellarator represents significant engineering complexity. The tokamak fusion reactors described in refs. 3 and 4 have coil systems which are at least as complicated as the classical stellarator. Perhaps it would be in order to reassess the relative merits of the stellarator and tokamak, particularly the simple and modular "twisted-coil" stellarator.

MIRROR MACHINES

The classical mirror machine has been a part of fusion research since its inception (see ref. 17), and consists of two regions of strong magnetic field separated by a region of weaker field, as shown in figure 27. The mirror field is generated by two coils, sometimes with a straight region of weaker uniform magnetic field between the two mirrors. In the mirror machine illustrated in figure 27A, the currents in the two coils are flowing in the same direction about the axis of symmetry. A variation of the mirror machine is the cusp, illustrated in figure 27B, and consists of two coils with oppositely flowing currents.

Both of these confinement devices rely on the fact that when particles move from a region of weak field to a region of strong magnetic field, a large fraction of the particles will be reflected from the regions of strong field if their velocity parallel to the axis is not too large relative to the perpendicular velocity. As long as charged particles remain in the confinement region in velocity space, they will reflect back and forth between mirrors indefinitely, unless collisions cause diffusion in velocity space and knock them into the "escape cone" which results in their loss out the ends of the mirrors. In the cusp geometry, the particles must be reflected not only from magnetic mirrors at either end, but also from the line cusp which encircles the axis halfway between the two mirror coils. The cusp geometry therefore has an additional route of escape for confined particles. This additional loss must be balanced against the improved magnetohydrodynamic stability of the cusp configuration, which arises because a particle sees a magnetic field increasing in all directions from the center of the confinement volume.

The classical mirror machines have significantly lower confinement times than toroidal devices. When confined particles undergo scattering collisions, they will be knocked into the escape cone and lost more rapidly than would be the case if they suffered classical diffusion across field lines to the walls. Toroidal devices are not subject to mirror scattering losses because their field lines close on themselves. As long as toroidal devices were subject to Bohm diffusion (see fig. 1), the confinement times of mirror machines were competitive with those of toroidal devices. In recent years, however, there has been a large and growing gap in the confinement times achieved which favors toroidal devices. It is now the consensus that the simple mirror machine cannot yield an economically feasible, net power producing fusion reactor. Therefore, its various modifications, discussed below, have been introduced to improve the confinement of the simple mirror machine.

Astron and Reversed Field Devices

The astron concept was first proposed in the mid-1950's (refs. 17 and 27) and consists of a geometry similar to that shown in figure 28. A long, solenoidal magnetic field is set up in the steady state. Relativistic electrons or ions are injected into this magnetic field and their energies are adjested so their gyrodiameters are comparable to the diameter of the intended plasma confinement region. The relativistic particles are caused to build up until the diamagnetic field generated by their motion exceeds that of the applied magnetic field. At this point, the magnetic field reverses inside the layer of particles, and closed magnetic field lines will encircle them. This layer is referred to as an e-layer or p-layer, depending on whether relativistic electrons or protons are used. The original Astron experiment was terminated in 1973 without having achieved more than about 15% of magnetic field reversal (ref. 27).

Subsequent experiments by Fleischmann and others at Cornell University (refs. 28 and 29) have injected relativistic electron into a pulsed mirror magnetic field and achieved a field reversal in this geometry. The essence of their approach is indicated on figure 29, and a photograph of their experiment is shown in figure 30. This same group has also proposed to use energetic protons to create field reversal (refs. 29 and 30), and a schematic reactor concept based on ion rings is illustrated in figure 31.

None of the reverse-field experiments operated so far have been steady state, but in principle they could be made so. The principal drawbacks of this approach are that cyclotron radiation from relativistic electrons severely limits the plasma energy density which can be confined by an e-layer device, and this has motivated proposals for using proton rings in the reverse-field configuration. Additionally, one must assure the stability of the e-layer or p-layer in addition to the confined plasma. The external equipment required to generate the e-layer or p-layer is very expensive and/or must be operated in a pulsed manner.

The 2XII B Experiment

The 2XIIB Experiment is a principal back-up approach in the ERDA fusion program (refs. 31 and 32.). The sequence of events in this experiment consists of injection of plasma from Marshall type plasma guns into a high vacuum region of relatively low magnetic field. The plasma is compressed in a minimum-B magnetic mirror machine (refs. 31 and 32). After being compressed to moderately high densities, the average ion energy is further increased by injection of several hundred equivalent amperes of energetic neutral particles with energies above 10 kV. The density is further increased by injection of neutral gas or a weak background plasma into the confinement volume.

This device (ref. 31) has achieved confinement times of up to 2 milliseconds, which is the maximum to be expected in view of particle scattering into the escape cone of this plasma. Earlier instability problems which plagued this approach (ref. 31) have been overcome. The results attained to date with this approach have been considered sufficiently encouraging that it may be scaled up to a much larger device (ref. 33) called the Tandem Mirror Reactor, in which additional confinement may be achieved by trapping the plasma in an electrostatic potential well. The only other major experiments resembling the general approach adopted for the 2XIIB experiments are the PR-7 machines (see ref. 34) in Russia.

Laser Heated Solenoid

The laser heated solenoid is primarily a concept for heating plasma and has been discussed in a review article by Kristiansen and Hagler (ref. 35). This concept consists of a very long linear pinch in which a sub-fusionable plasma is created by shock heating and compression typical of pinch devices. If a non-monotone radial density profile can be produced, such that the plasma is hollow with an annular shell of higher density, it is possible to irradiate the plasma with a laser along its axis in such a way that the laser radiation is refracted within the plasma. The plasma behaves as a light pipe until the radiation is absorbed and the plasma is heated to fusion temperatures. Studies of this concept have shown that the length of solenoid required is on the order of hundreds of meters or several kilometers. This concept is burdened with all the difficulties of pinch reactors (ref. 36), including high capital costs, the necessity of using magnetic fields above 10 Tesla, and the problem of storing energy for the pulsed coils of the pinch.

The LITE Experiment

Another concept for producing a fusion-like plasma in a mirror machine is the LITE epxeriment (Laser Ignited Target Experiment) (ref. 37). The magnetic field is a "baseball" minimum-B mirror geometry, similar to but smaller than the original baseball experiment at Livermore, the field winding of which is shown in figure 32. In the LITE experiment, it is proposed to fill a minimum-B geometry with plasmas of fusion interest by heating a small pellet of solid fuel, suspended in the center, with a laser beam. This approach provides an alternative way in which plasmas of fusion interest can be heated by lasers, but its feasibility for eventual net power producing fusion reactors is problematical, because of the rapid particle losses associated with the minimum-B geometry, and the relatively poor efficiency of lasers as a plasma heating method.

The KAKTUS-SURMAC Concept

In the KAKTUS-SURMAC concept, magnetic dipoles are arranged around the periphery of the intended containment volume, resulting in a cusp-like containment geometry in which the bulk of the plasma is contained in regions of nearly zero magnetic field. The plasma perceives a magnetic field which increased rapidly in strength as particles approach the walls where magnetic dipoles are located. The major loss in this geometry is along the cusps of the magnetic fields.

The concept of using multiple magnetic dipoles to confine a plasma in a nearly zero field region was put forward by M. Sadowski, who developed the "KAKTUS" concept in the mid-1960's (ref. 38 and 39). The KAKTUS device is shown in figure 33, and consists of 32 pulsed dipole coils, driven by a capacitor bank, arranged over the surface of a sphere. This general approach was later adopted by Leung and his associates at UCLA in the SURMAC concept (refs. 40 and 41). In the SURMAC, the multipolar magnetic fields are generated by wires or permanent magnets arranged over the surface of the vacuum vessel in which the plasma is confined. A diagram of one of the SURMAC devices with conductors wrapped around the containment volume is shown in figure 34. The SURMAC concept has been proposed as a possible fusion reactor (ref. 42), based on scaling laws theoretically derived from a consideration of the cusp losses. The multipolar cusp configuration for a linear version of such a reactor is illustrated in figure 35.

The KAKTUS-SURMAC concept offers the interesting possibility of confining a plasma in a region of low or zero magnetic field. This would avoid cyclotron radiation losses, and also minimize the capital investment required to produce the confining magnetic field. At the present time, however, it is not clear that a dense energetic plasma of fusion interest can be confined in such a geometry without unacceptable losses along the cusps of the magnetic fields.

BUMPY TORI

The Classical Bumpy Torus

The classical bumpy torus is illustrated on figure 36 and consists of a number of coils equally spaced in a toroidal array. Each sector of the torus consists of a magnetic mirror. The particles which are confined by this geometry are of two kinds: those which reflect back and forth between the magnetic mirrors in an individual sector, and those which circulate around the major circumference of the toroidal plasma. The magnetic field gradients along the toroidal direction result in particle drift surfaces which close on themselves for both trapped and passing particles. This geometry represents an evolution of the simple mirror machine, in which several magnetic mirrors are placed end to end in a toroidal array to confine particles that would otherwise be lost through the mirrors.

The classical bumpy torus was proposed by Gibson, Jordan, and Lauer (ref. 43), who later performed an extensive series of investigations of single particle motion relevant to this geometry (ref. 44). Somewhat later Geller (refs. 45 and 46) operated a pulsed plasma source in a bumpy torus geometry and reported near classical confinement of the after-glow plasma. Fanchenko, et al. (ref. 47) have investigated turbulent heating in a bumpy torus plasma.

The classical bumpy torus offers a simple coil configuration, in which failed coils can be replaced relatively easily, and without having to be concerned about poloidal windings threading the inner bores of the toroidal field coils. The relatively wide spacing of the coils allows good access to the plasma volume for pumping, divertors, or injection and heating devices.

Hot Electron Bumpy Torus

Dandl and co-workers (refs. 48 and 49) have carried out experimental investigations on electron cyclotron resonance heating in the Oak Ridge ELMO Bumpy Torus device. The ELMO creates a stable magnetic well in each sector of the torus with high beta, hot electrons which are generated by absorption of RF power; the ion population is heated by binary collisions with the more energetic electrons. Relativistic electrons, which are generated by RF heating, are trapped near the midplane of each sector of the ELMO Bumpy Torus and produce beta values exceeding .5 in steady-state operation (refs. 48 and 49). This provides encouraging experimental evidence that stable, high-beta plasmas can be confined in the bumpy torus configuration, at least when circulating relativistic electron currents are present. Figure 37 shows a cutaway diagram of the ELMO Bumpy Torus Experiment, which consists of a total of 24 coils in a toroidal array. Figure 38 shows the vacuum magnetic field without the relativistic electron rings, and figure 39 shows the perturbed magnetic field when the relativistic electron rings are present. The direction of the magnetic field on the axis of the ELMO device is not reversed, but it sufficiently perturbed to overcome flute and other magnetohydrodynamic instabilities that would otherwise be expected in the simple bumpy torus configuration. The geometry of the magnetic field windings is modular, implying an engineering advantage. An additional advantage is the demonstrated ability of the ELMO Bumpy Torus to stably confine a high beta plasma in the steady state.

Toroidal Minimum-B Configurations

The stable magnetic well generated in the ELMO Bumpy Torus and illustrated on figure 39 has the disadvantage that the relativistic hot electrons which generate the magnetic well must be produced by relatively inefficient RF heating. Such hot electrons also account for most of the plasma energy density, without contributing to fusion reactions. An attractive way of confining a high beta toroidal plasma without relativistic electron rings is to use a toroidally linked system of minimum-B magnetic mirrors. Such a system of minimum-B mirrors can provide magnetohydrodynamic stability with conductors located outside the plasma volume. This approach was examined by Cordey and Watson (ref. 50) and later by Ohasa and Ikuta (ref. 51). The approach described in ref. 51 is illustrated in figure 40, which shows a single coil of the toroidally linked system. The view shown is from the top of the coil, with the dotted lines representing the portion of the coil below its equatorial plane. Figure 41 shows how 13 of these coils would be arranged in a toroidal array. Note that the coils are rotated with respect to each other as one moves around the torus, thus giving rotational transform to the configuration. Figure 42 shows a magnetic field plot of iso-intensity contours in the equatorial plane of the torus, and figure 43 shows iso-intensity contours in various vertical planes. The toroidal minimum-B configurations described in refs. 50 and 51 are theoretical studies. It does not appear that this confinement geometry has been reduced to practice.

These toroidally linked minimum-B coils preserve the modular nature of the classical bumpy torus, but at a cost in increased difficulty of winding the individual coils. However, they do appear to offer the possibility of confining toroidal plasmas in the steady-state without the penalties associated with generating relativistic hot electrons.

ELECTROSTATICALLY ASSISTED CONFINEMENT

Since the beginning of controlled fusion research, pure magnetic containment, in which a plasma is confined solely by strong magnetic fields, has been the dominant approach. Externally applied electric fields have not thus far played a significant role in toroidal plasma confinement. The difficulties of principle in the way of using electric fields for confinement were summarized in an early paper by Post (ref. 52), who discussed the implications of Earnshaw's theorem. This theorem states that a static distribution of charge, acted on only by electric forces, cannot rest in stable equilibrium in an electric field. It follows from this that it is not possible to confine a plasma of fusion interest with electric fields alone. Earnshaw's theorem is sometimes misunderstood as completely ruling out the utility of externally applied electric fields in the confinement of fusion plasmas. It does not prohibit a distribution of charges from existing in dynamic equilibrium in the manner of the electrostatic containment experiments to be described below, and it does not imply that electric fields cannot be used to enhance the confinement properties of magnetic containment configurations.

Pure Electrostatic Containment

Several experiments have been conducted to explore the electrostatic containment of charges of a single polarity in dynamic equilibrium (refs. 53 to 57). The general approach is illustrated by the schematic drawing in figure 44. A typical electrostatic containment experiment consists of two or more spherical grids with electron or ion sources located on the outermost grid. The inner spherical grid is biased to high voltage to provide acceleration of the charged particles and to create an electrostatic potential well. The particles are accelerated along a radial direction. Upon reaching the interior of the grids, the particles coast along a diameter of the sphere and are decelerated when they pass into the electric field at the opposite end of the diameter. The radial oscillation of the charged particles will be repeated until they finally intersect the grid wires and are lost. High localized densities near the center of such spherical geometries have been reported (ref. 54).

It does not appear that pure electrostatic containment can compete with other containment concepts because of electrical breakdown problems, and also because the particles intersect the grid wires and are lost on a relatively short time scale. It does offer the advantage of steady-state operation, and the absence of expensive magnetic field coils.

Electrostatically Stuffed Cusps

The use of a combination of electric and magnetic fields to confine a plasma is implied by some early work on magnetically contained arcs done at the Oak Ridge National Laboratory (ref. 17) and was explicitly discussed in an early paper by George in 1961 (ref. 58). Several investigators (refs. 59-61) have applied strong electric fields to a plasma in a cusp magnetic geometry to enhance plasma confinement. In these experiments, electrodes are placed at the throats of the magnetic mirrors and at the circular line cusp in the midplane. The placement of electrodes in a typical cusp experiment is illustrated in figure 45, and the resulting electrostatic potential well in figure 46. Electric fields are used to reflect ions and/or electrons which would otherwise be lost along the magnetic field lines. The electrostatically plugged cusp geometry has been suggested as a possible approach to a fusion reactor (ref. 62).

The electrostatically stuffed cusp geometries offer the advantage of a magnetohydrodynamically stable magnetic configuration, in which the plasma sees a magnetic field which increases in all directions from the center of the confinement volume. The application of electric fields has reduced losses, and increased the plasma density by a factor of 10 in the KEMP II experiment (ref. 60). This approach is capable of being operated in the steady state, the decreased magnetic field at the center of this geometry may reduce cyclotron emission from the plasma and thus make advanced fuel cycles possible, and the smaller total volume may make possible power plants with a relatively small total output.

Electrostatically Stuffed Mirrors

Externally applied electric fields have also been used to enhance the heating and confinement of a magnetic mirror geometry (refs. 63 to 66). These experiments do not make any provisions to suppress a possible MHD instability of the magnetic mirror geometry. Instead, they attempt to use a series of electrodes at, or just outside the magnetic mirror throats to reflect ions and/or electrons, which would otherwise be lost along the field lines. This concept eliminates the line cusps at the midplane along with possible losses along it.

Moir et al. (ref. 63) attempted to improve only the confinement of a mirror machine by an arrangement of electrodes in the mirror throats similar to that illustrated in figure 45 for the cusp geometry. The "Burnout" series of experiments at Oak Ridge used radial electric fields acting on a mirror plasma (ref. 64), but their primary function was to heat the plasma rather than improve confinement. The Burnout experiments were followed up at the NASA Lewis Research Center in the HIP-SUMMA series of experiments (refs. 65,66). A photograph of the superconducting SUMMA magnet facility is shown on figure 47, and a photograph of a characteristic electrode assembly is shown in figure 48. Steady-state plasmas have been created in the SUMMA facility with densities up to $10^{13}/cm^3$, and, under lower density operating conditions, ion kinetic temperatures up to several kilovolts have been observed.

Possible drawbacks of this approach include MHD instabilities and confinement of the plasma in a region of higher magnetic field than would be the case in a cusp geometry. This latter consideration may rule out advanced fuel cycles or operating regimes that require little or no cyclotron emission from the plasma.

Electrostatically Assisted Toroidal Confinement

Externally imposed electric fields have not been used to influence toroidal confinement until recently. A theoretical paper by Kovrizhnkyh (ref. 67) examined the effects of an ambipolar electric field on radial transport in tokamaks, stellarators, and bumpy tori. This work was later extended by the same author (ref. 68). A paper by Stix (ref. 69) examined the confinement implications of ambipolar electric fields in toroidal geometries.

The only experiment in which electric fields are deliberately applied to a toroidal plasma appears to be the Bumpy Torus experiment at the NASA Lewis Research Center in Cleveland, Ohio (refs. 70-72). The approach taken in this experiment is characterized by three factors: 1) The magnetic field and the plasma heating mechanism are operated in the steady state, 2) Strong magnetic <u>and electric</u> fields are applied to the plasma, and 3) The ion kinetic temperatures are typically more than a factor of 10 higher than the electron temperatures in this plasma.

An isometric cutaway drawing of the NASA Lewis Bumpy Torus is shown in figure 49. The 12 superconducting magnets are shown. Each magnet can generate up to 30 kilogauss at its throat. The entire torus of plasma is raised to high potentials by electrode rings which surround the plasma at the midplanes between the magnetic field coils. Figure 50 shows a schematic drawing of the Bumpy Torus plasma and its associated radial electric fields. The vertical element at the center is a midplane electrode ring, which is typically operated at tens of kilovolts. The high potentials result in strong radial electric fields between the plasma and the grounded magnet dewars. The strong crossed electric and magnetic fields in the plasma volume cause drifts of ions and electrons which heat the ions to kinetic temperatures of kilovolts.

One interesting consequence of the application of strong external electric fields is that the radial transport of charged particles is greatly affected by the direction in which the radial electric field points. Some data are shown in figure 51 for a paired comparison test in which the magnetic field, neutral background pressure, electrode voltage, and electrode geometry were the same, only the plasma was biased in the one case to positive polarities, and in the other case to negative polarities. The plasma density and containment time is about a factor of 20 higher with the negative polarities, when the electric field pointed radially inward, than when the polarity was positive, and the electric field pointed outward from the plasma. In the former situation, ions were "pushed into" the plasma by the electric field, and outward in the latter. These data illustrate quite clearly that the direction of the electric field has a major effect on plasma containment, but it remains to show whether values equaling or exceeding classical diffusion are feasible.

The electric field serves a double function; it not only heats the ions by E/B drift, but it also can have a very beneficial effect on the plasma containment. The basic bumpy torus magnetic field is modular and allows good access to the plasma volume. One of the potential engineering drawbacks is the presence of the midplane electrode rings, shown in figure 50, which are required to bias the torus of plasma to high potentials. Whether or not such water-cooled electrode rings can be maintained in the vicinity of a fusion plasma remains to be seen.

MISCELLANEOUS APPROACHES

The Migma Concept

The migma concept for controlled fusion represents a combination of three ideas: the colliding beam storage ring concept from high energy nuclear physics, the organized motions found in magnetrons and triode vacuum tubes, and the energetic neutral injection concept from mirror machine research. This concept has been conceived and promoted by B.C. Maglich and his co-workers (refs. 73-75). The essence of this concept is illustrated on figure 52. Energetic neutrals are injected into a magnetic field and ionized in such a way that they gyrate in circles shown in figure 52A. These gyrating particles can be made to precess about the magnetic axis as is illustrated in figure 52B. Once a large number of particles are accumulated and gyrating around the magnetic axis, the situation illustrated in figures 52C and D will result. Many of the particle orbits which intersect the axis will result in head-on collisions between individual charged particles and these can produce a large number of fusion reactions in a small volume near the magnetic axis, as illustrated in figure 51D. MeV particle energies are required in order to make the fusion cross section large compared to the elastic scattering cross section. More complicated orbits are possible, in which particles can be made to gyrate and drift in such a way that the intersection of their orbits occurs in several locations in the plasma volume. Figure 53 shows a photograph of the migma experiment, in which the superconducting magnets which produce the uniform field of this device are shown.

If the migma concept works as is intended, fusion reactions will occur in a relatively small volume where the colliding orbits are concentrated, and the total power output will be relatively small. It remains to be shown that a plasma of sufficiently high density can build up without disrupting the particle orbits and preventing the formation of regions of intersecting orbits. It also remains to be shown that the migma plasma can build up to densities higher than those achieved in neutral injection experiments, which were limited by plasma instabilities. It is clear that the migma concept will require a large amount of circulating power to provide the energetic charged particles with more than an MeV of energy, and this may not be possible with high efficiency.

The Wall-Confined Plasma

It has been suggested that a reacting fusion plasma be confined by gasdynamic boundary layers alone, or by such boundary layers in conjunction with magnetic fields. This suggestion appears to have been first made by Tsien in 1956 (ref. 76), who developed an analogy between a fusion reactor and a chemical rocket engine, and concluded that it may be possible to confine a fusion reaction with gasdynamic boundary layers. A similar concept was put forward by Alfven and Smars (ref. 77), who proposed to shield a steady-state magnetically-confined plasma by a layer of neutral gas near the wall, making use of the lower thermal conductivity of the neutral gas relative to that of the ionized central core. Gross (ref. 78) has proposed a pulsed concept, in which a plasma is heated to densities and temperatures of thermonuclear interest in a shock-tube, and then confined by a suddenly imposed magnetic barrier which retards the dissipation of this gas The essence of this concept is shown in figure 54. The shock wave propagates from left to right, reflecting off the end of the shock tube on the right. After the passage of the shock wave, the heated gas at the right hand side of the shock tube is confined by a "magnetic dam" which is generated by a pulsed coil with a fast rise time. The magnetic and plasma energy densities associated with this concept are illustrated on figure 55 It is unclear whether any of these concepts could be capable of producing a plasma of fusion interest for a significant length of time.

SUMMARY

An attempt has been made in Table IV to summarize the advantages and disadvantages of the alternative confinement concepts covered in this survey. It is too early to state which, if any, of the advanced concepts described in this table will be feasible or will find their way into the mainstream of fusion research. Many of these concepts have one or more attributes which make them a potential improvement over the tokamak concept, in terms of environmental acceptability or of capital and resource productivity. Further research on these concepts may reveal difficulties not listed in this table or might overcome some of the disadvantages listec One should guard against any tendency to consider all approaches listed on Table IV as equally feasible or equally plausible alternatives to the tokamak. Most have little or no data base, in contrast to the very great depth of the experimental and theoretical effort on the tokamak concept. To give a crude indication of this factor, three additional rows have been added at the bottom of Table IV. The first row on the bottom of Table IV indicates the concepts which have been reduced to practice in the form of operating experimental apparatus. The second row indicates the approaches for which the scaling laws of the Lawson parameters are reasonably well known, and the last row lists those approaches for which density, ion temperature, and containment time have been measured.

Table V lists the plasma parameters of some of the experimental devices based upon the concepts listed in Table IV. Insufficient data are available from the literature to list entries for many of the devices known to be operational. Figure 56 is the Lawson diagram for the alternative approaches listed in Table V. In most cases shown on Table IV and Figure 56, simultaneous values of n, τ, and T_i were not available, and it was not clear whether the particle or energy containment time was being quoted. Comparison of this with figure 2, the Lawson diagram for tokamak experiments, shows that many of the alternative approaches have to advance more than two orders of magnitude in the parameter $n\tau$ before they can be considered competitive with the larger and much better funded tokamak experiments.

TABLE V

PLASMA PARAMETERS OF ALTERNATIVE DEVICES

DEVICE AND TYPE	Te, eV	Ti, eV	n_{emax}	τc, msec	ne τc
KEMP II - Electrostatically Plugged Cusp	1000	-	4×10^{11}	0.5	2×10^{8}
Torso Torsatron	200	-	10^{13}	0 3	3×10^{9}
Columbia High Energy Shock Tube	100	1000	10^{16}	-	-
Tormac	10 eV	350	2×10^{15}	0.1	2×10^{11}
2XIIB Pulsed Mirror	250	13,000	3.5×10^{13}	2 0	7×10^{10}
Lewis Bumpy Torus	10 eV	200-400	6.2×10^{12}	2.5	1.6×10^{10}
ELMO Bumpy Torus	100	130	2.0×10^{12}	20	4×10^{10}
Proto-Cleo Stellarator	10 eV	10 eV	2×10^{12}	1.5	3×10^{9}
Sirius Stellarator	1000	-	10^{13}	1.0	10^{10}
Uragan Stellarator	300	400	2×10^{12}	0 6	$1 2 \times 10^{9}$
C - Stellarator	70	400	2×10^{13}	1.0	2×10^{10}

If it were possible to generate fusion-electric power with 1/10 the amount of capital or resources of competitive approaches, there would obviously be an even greater motivation to develop fusion power plants than now exists. Such a situation may be possible for fusion power plants using advanced fuel cycles, and the possiblity has already been shown to exist in the area of space propulsion (ref. 3), where fusion propulsion can make possible missions which otherwise could not be accomplished at all.

Design studies of electrical generating plants based on the DT Tokamak reactor have been encouraging in that they have shown that such a power plant may be feasible, but they have been somewhat discouraging in that they have indicated such power plants will not have a capital cost lower than existing alternative power plants (refs. 4, 6, and 7). Until the present time, the focus of fusion research has been on whether fusion reactors are feasible at all. In the future, answering the question of feasiblity will not be sufficient. Those of us in the fusion community must be able to show, in addition, that its capital and resource productivity, as well as its environmental acceptability, are at least as good as alternative energy sources.

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FIGURE CAPTIONS

Figure 1	Containment time in toroidal devices for the years 1952-1970 from Eastlund and Gough, Wash 1132.
Figure 2	Lawson diagram for tokamaks. The solid circles are operating experiments; the open circles are planned feasibility experiments.
Figure 3	Conductor geometry of the TORMAC concept.
Figure 4	Photograph of the TORMAC plasma.
Figure 5	Conductor configuration of the topolotron concept.
Figure 6	Magnetic field lines at the surface of the topolotron plasma. Note the limit cycles at the top and bottom of the interior circumference of the torus.
Figure 7	Poloidal component of magnetic field in the topolotron.
Figure 8	Photograph of the topolotron apparatus in an early stage of assembly.
Figure 9	The plasma and conductor configuration of the EXTRAP concept.
Figure 10	The magnetic field of a simple torus.
Figure 11	Geometry of the figure 8 stellarator.
Figure 12	Windings of the classical stellarator.
Figure 13	Magnetic field contours and a drift surface for the L=3 Proto-Cleo stellarator.
Figure 14	Experimentally determined drift surfaces in an L=3 stellarator.
Figure 15	Photograph of an early racetrack stellarator.
Figure 16	Photograph of the Wendelstein W-VII Stellarator.
Figure 17	Isometric cutaway drawing of the Proto-Cleo stellarator.
Figure 18	Windings and vacuum tank of a ℓ=1 torsatron.
Figure 19	Windings of the Culham Torsatron.
Figure 20	Drift surfaces of the Culham Torsatron.

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TABLE IV. - RELATIVE MERITS OF ALTERNATIVE APPROACHES TO PLASMA CONFINEMENT

	Tokamak	Tormac	Topolotron	Extrap	Classical Stellarator	Torsatron	Twisted-coil Stellarator	Reversed field devices	2xII B concept	Laser heated solenoid	LITE concept	Kaktus-surmac	Classical bumpy torus	Electric field bumpy torus	ELMO bumpy torus	Toroidal minimum-B configurations	Electrostatic containment	Electrostatically stuffed cusp	Electrostatically stuffed mirror	MIGMA	Wall-confined plasma
Advantages:																					
High beta		✓	✓	✓				✓	✓	✓		✓			✓		✓	✓		✓	
Improved stability		✓	✓	✓					✓		✓	✓			✓	✓		✓			✓
Low capital cost		✓	✓	✓		✓	✓					✓	✓	✓	✓		✓	✓	✓		✓
Steady-state operation					✓	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	
Simple coil geometry				✓		✓	✓	✓		✓	✓		✓	✓	✓		✓	✓	✓	✓	
"Force-free" coil geometry						✓															
Advanced fuel cycles												✓		✓				✓		✓	
Disadvantages:																					
Low beta	✓				✓		✓														
Cyclic operation	✓		✓	✓				✓	✓	✓	✓										
Possible cusp or mirror leakage		✓	✓						✓	✓	✓	✓						✓	✓		
Complex magnetic coils	✓	✓	✓		✓				✓							✓					
Costly heating or injection equipment	✓								✓	✓	✓				✓		✓			✓	✓
Reduced to practice	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
Scaling laws known	✓				✓				✓						✓						
Lawson parameters measured	✓	✓			✓				✓					✓	✓			✓		✓	

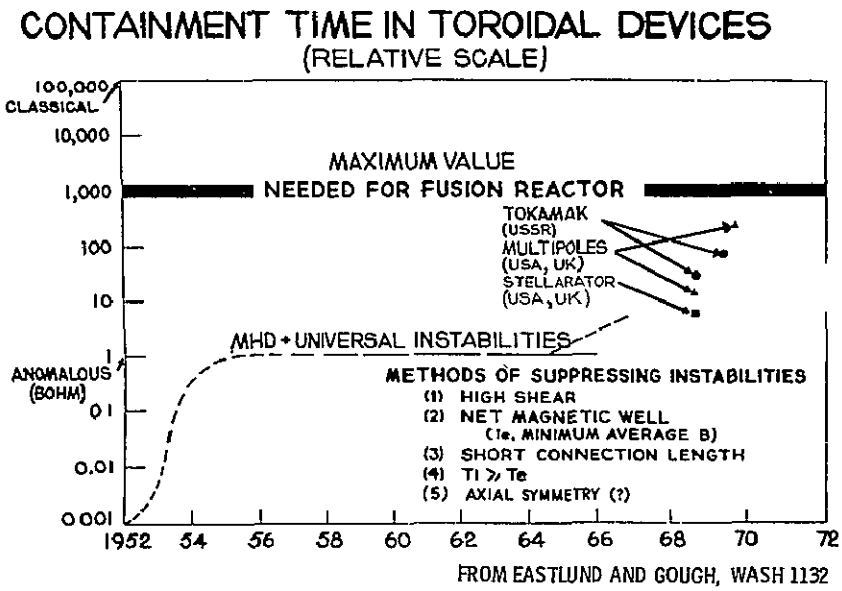

Figure 1.

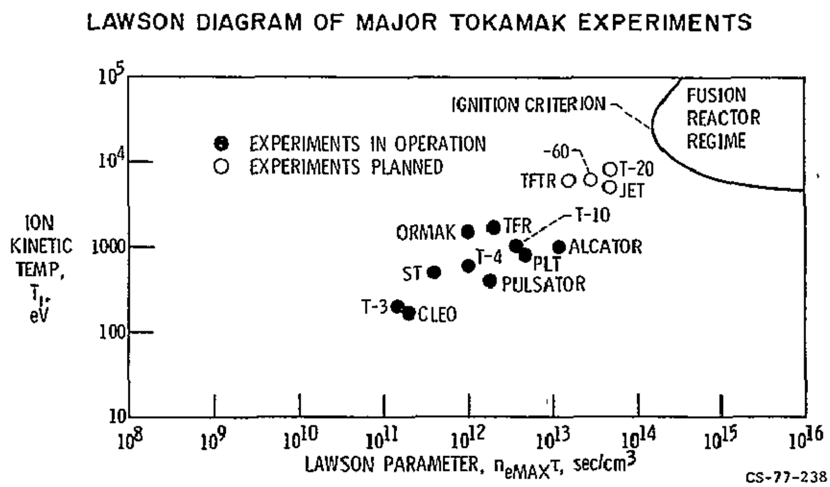

Figure 2

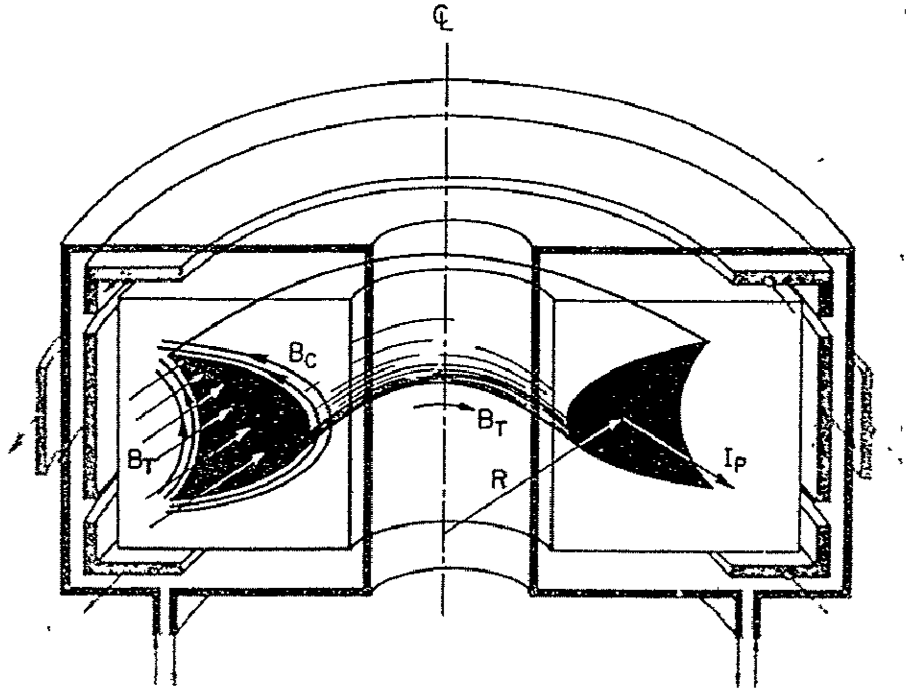

Figure 3.

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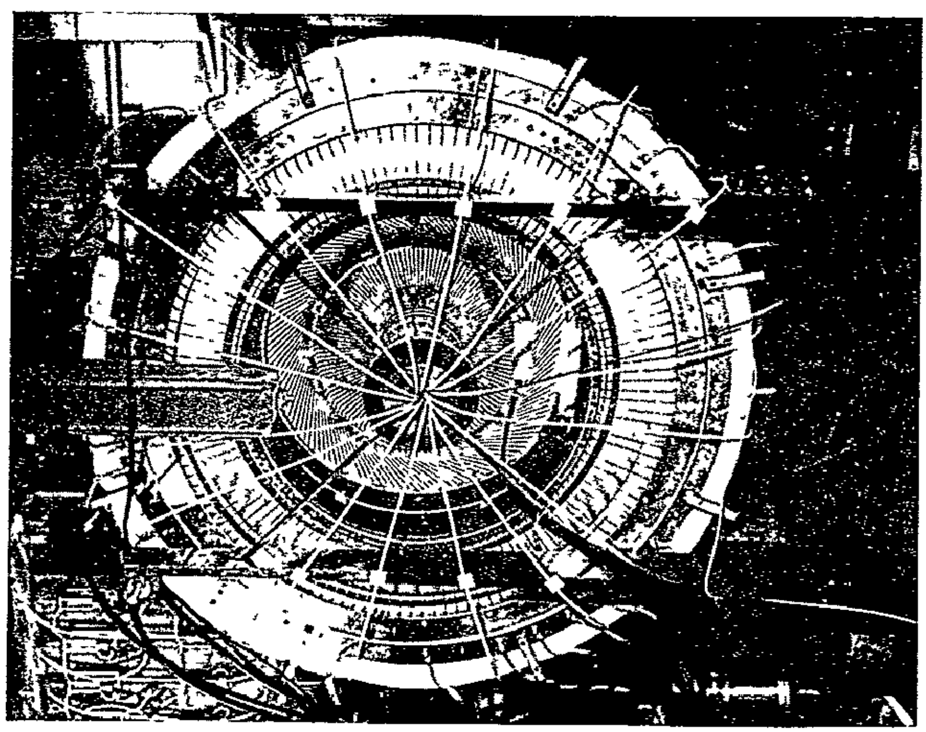

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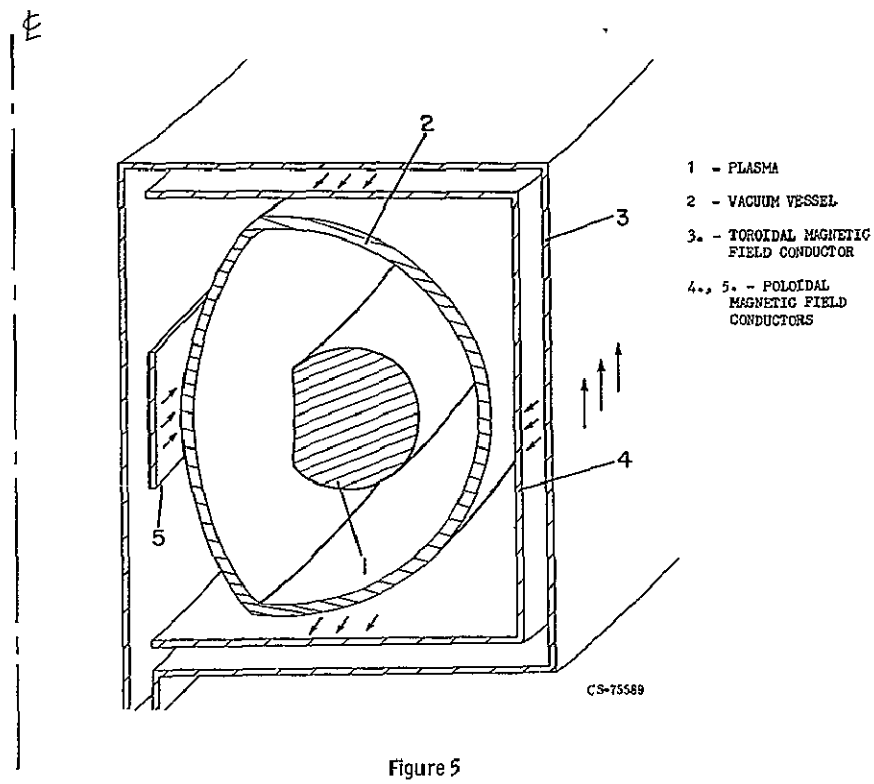

Figure 5

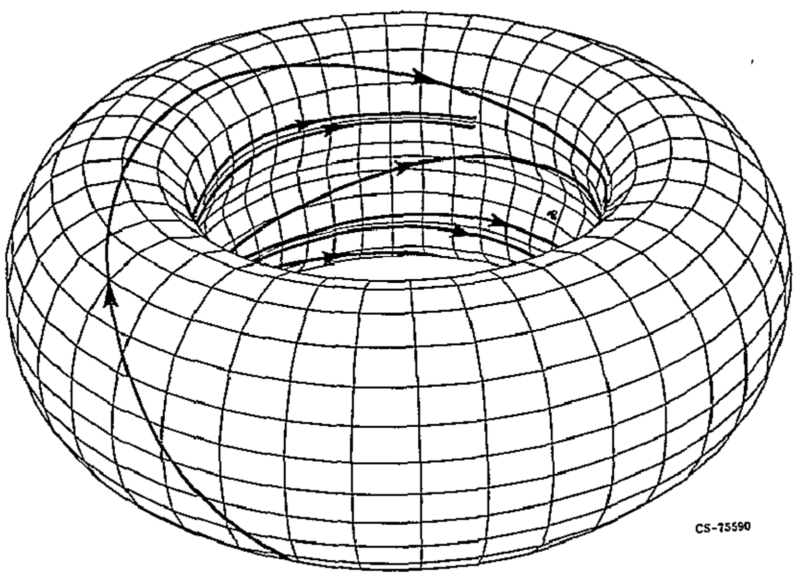

Figure 6

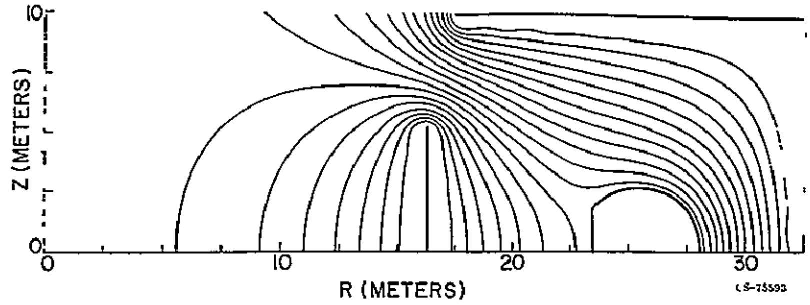

Figure 7.

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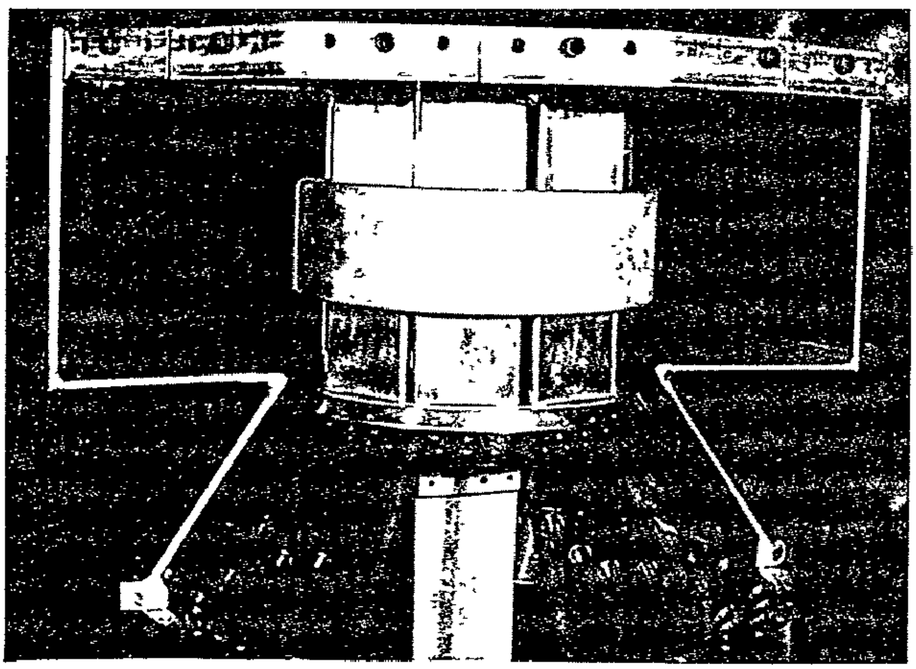


Figure 8

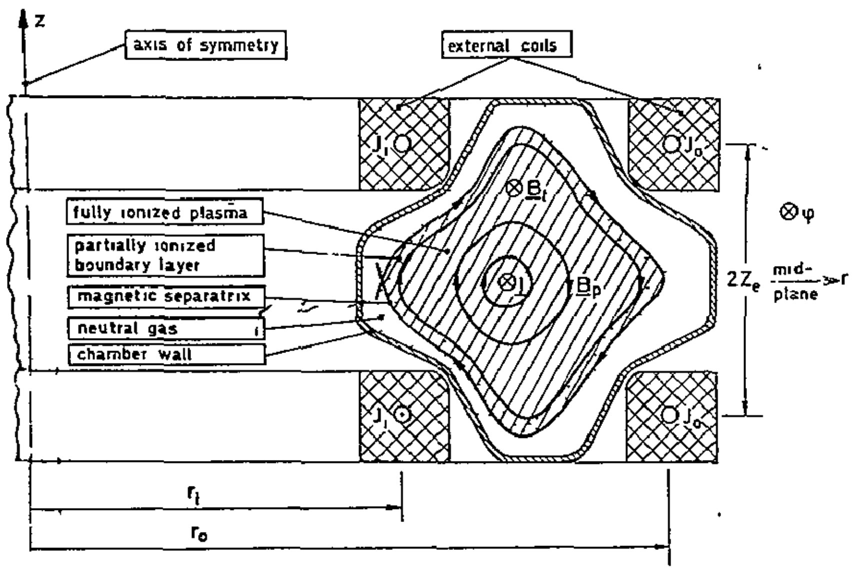
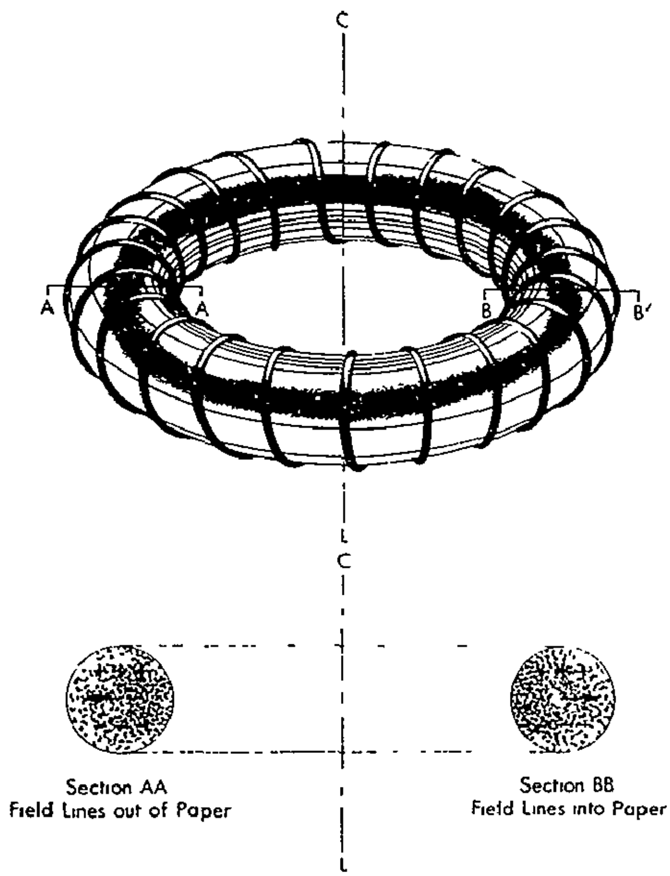


Figure 9



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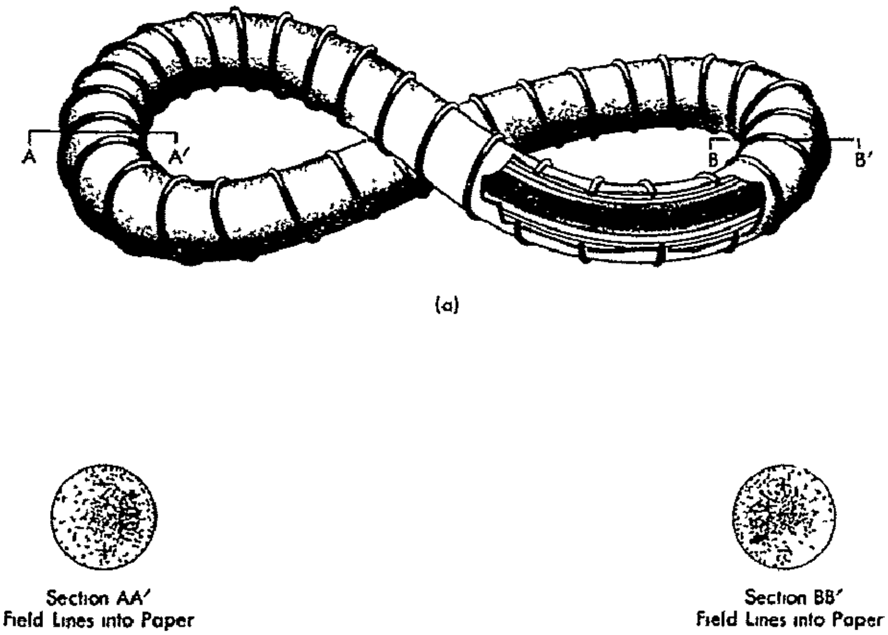

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Figure 11.

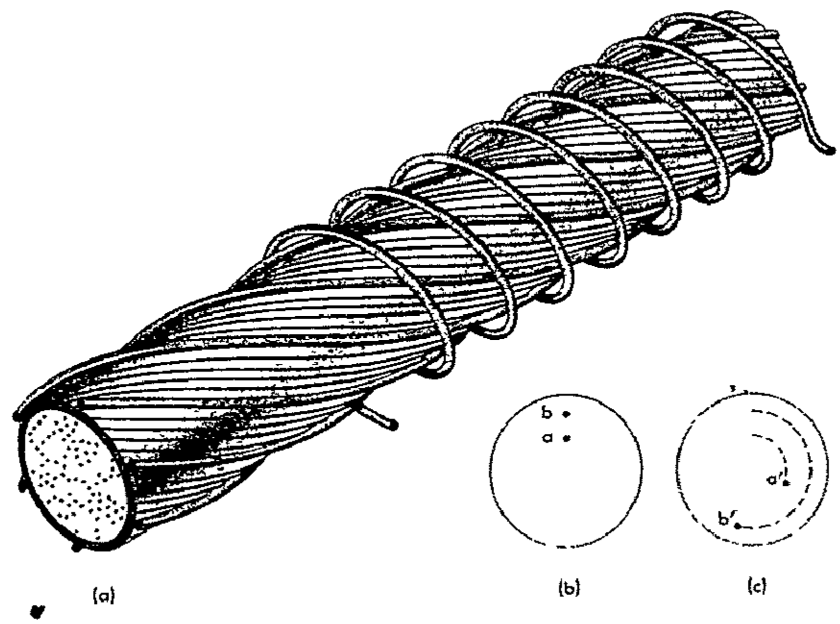


Figure 12.

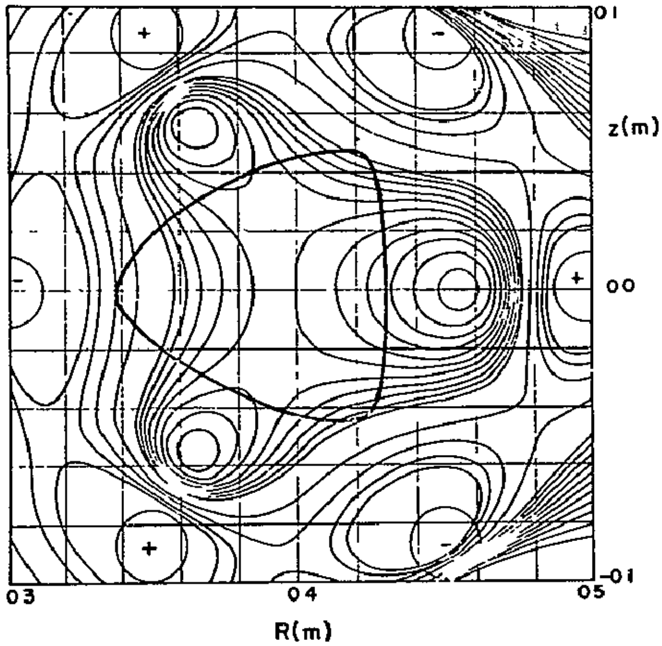
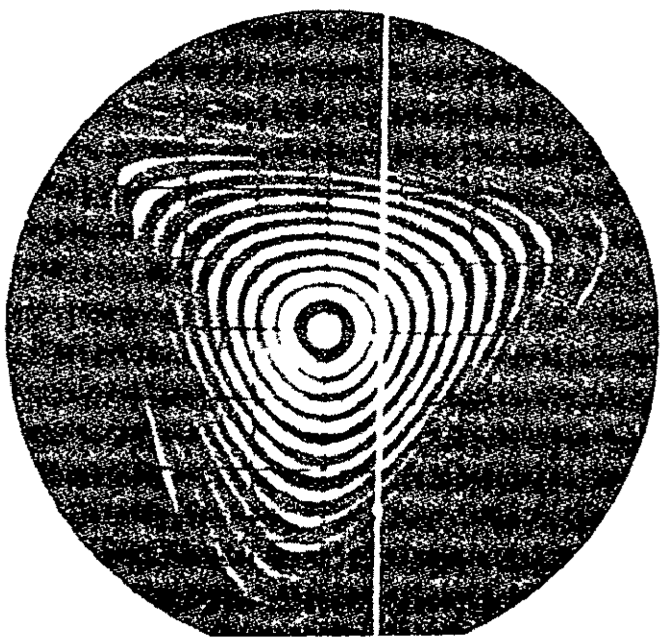


Figure 13.



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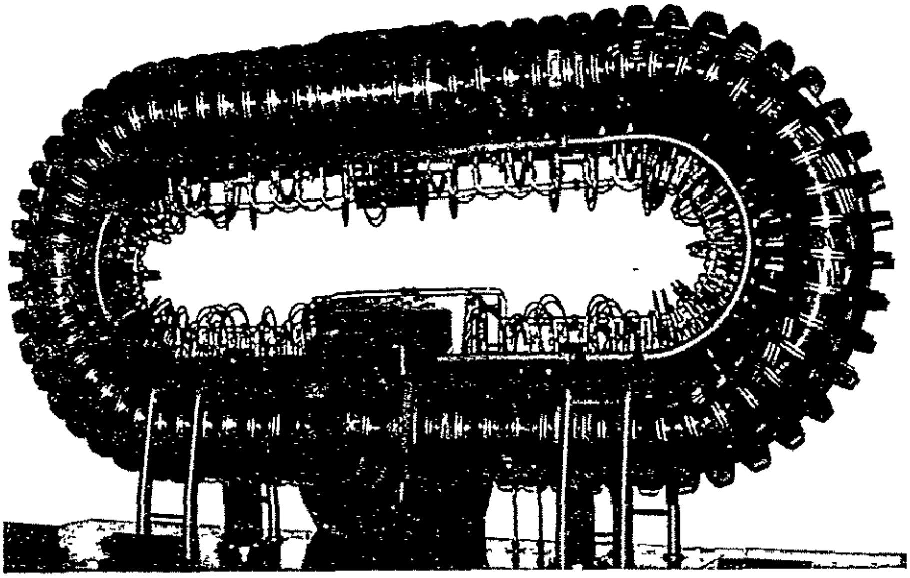

Figure 15.

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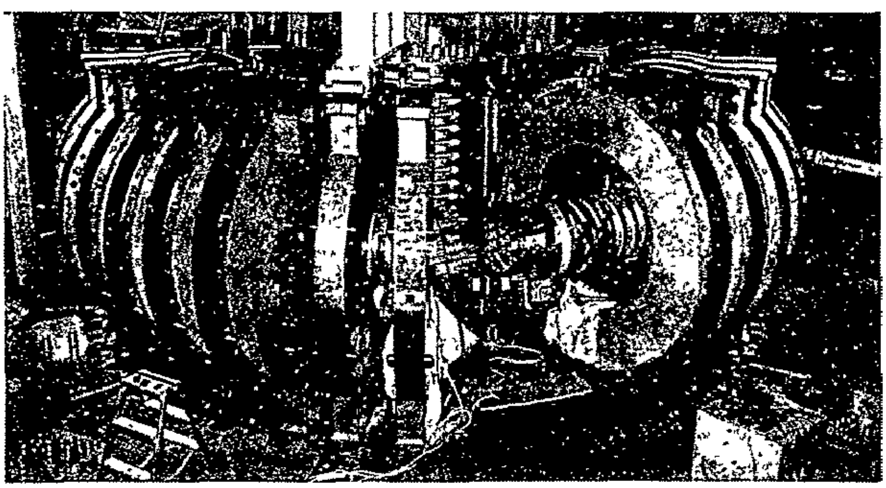

Figure 16

PROTO-CLEO Stellarator . shown with Medium-Magnetic Shear Helical Winding.

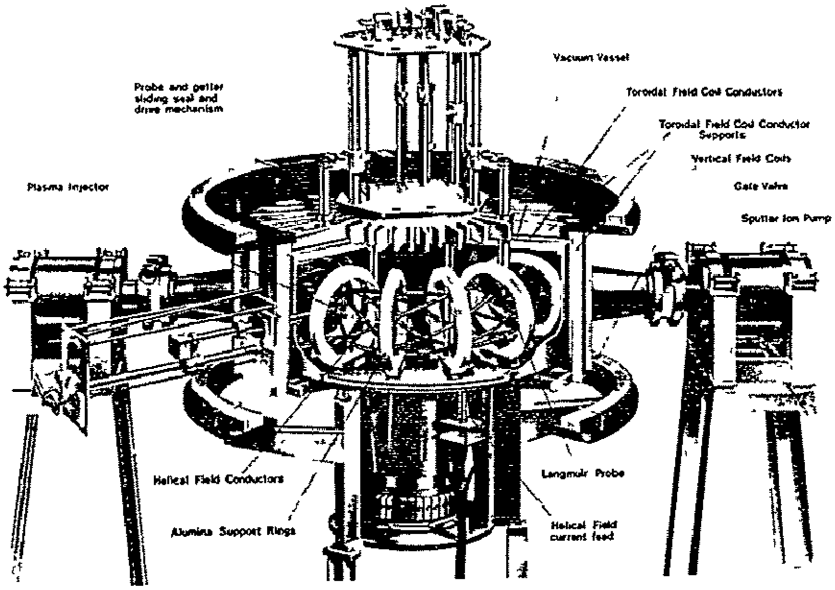

Figure 17.

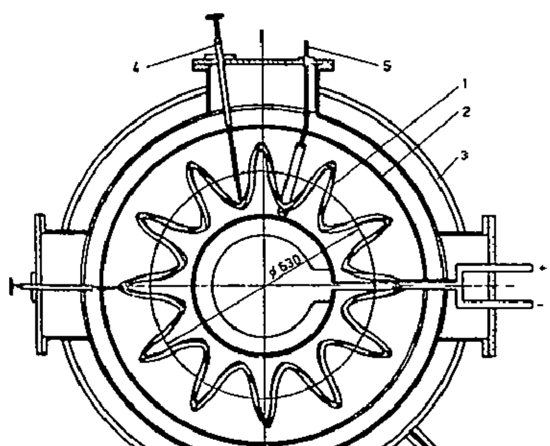

Figure 18 – Diagram of the Torsatron experiment: (1) helical winding, (2) force shell, (3) vacuum chamber, (4) electron gun and local probe; (5) circular electrostatic probe

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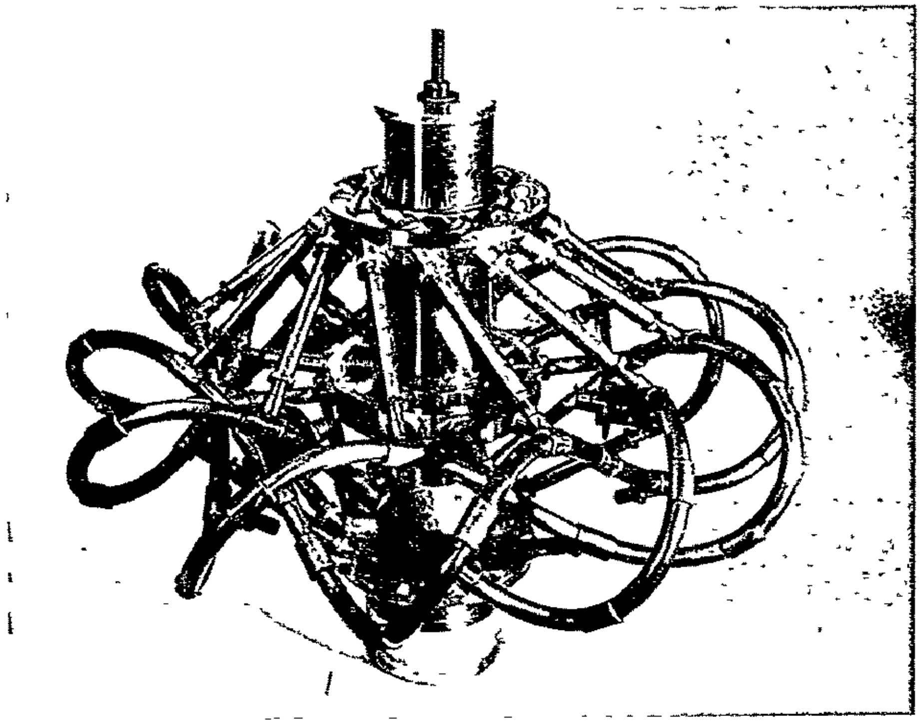

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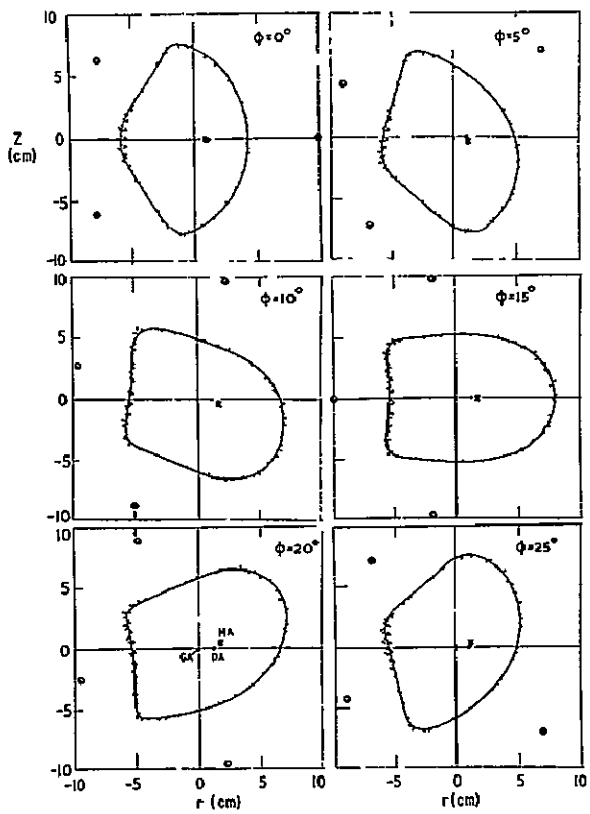
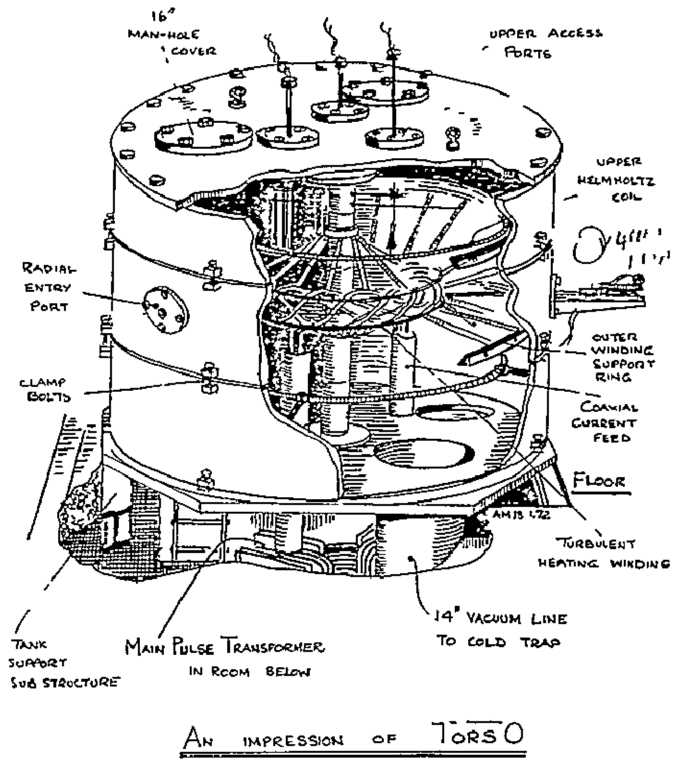


Variation of magnetic surfaces as a function of ϕ_f showing position of magnetic, geometric, & displaced axes

Figure 20.



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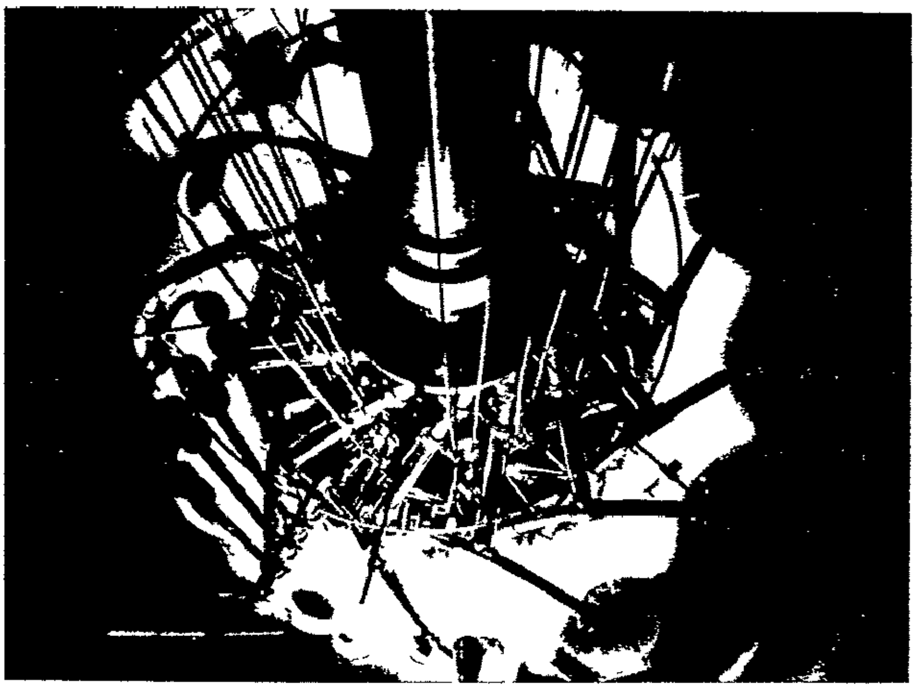

Figure 22.

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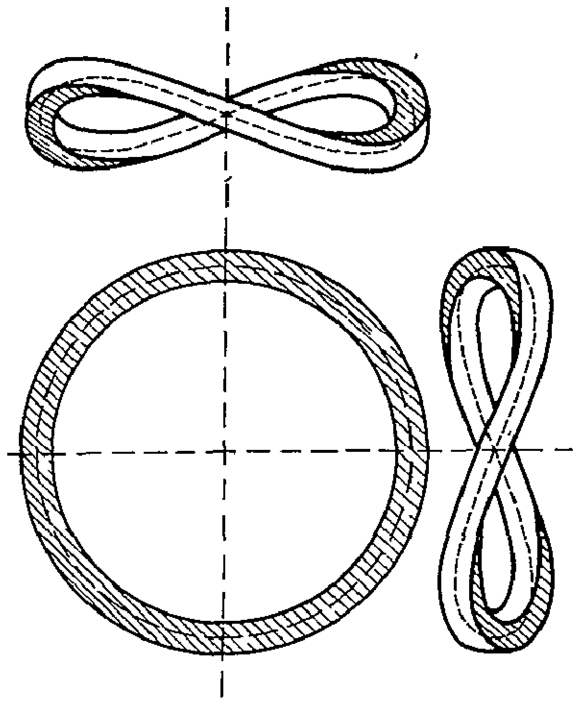

Figure 23

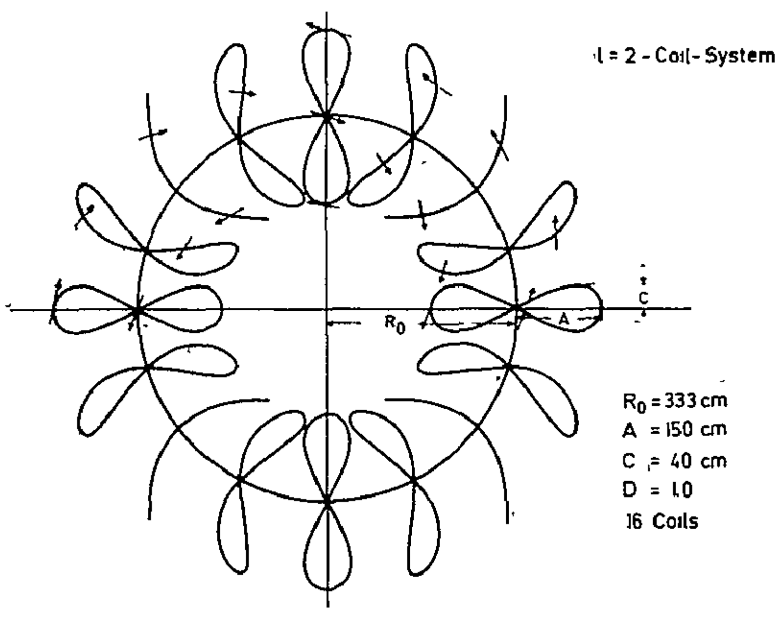

Figure 24

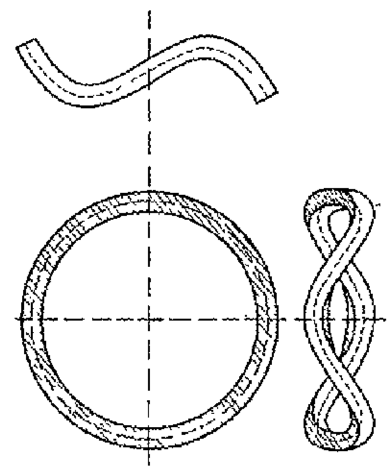

Figure 25

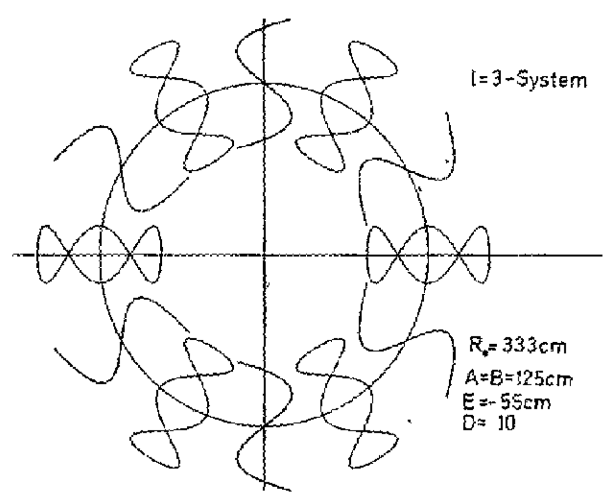

Figure 26

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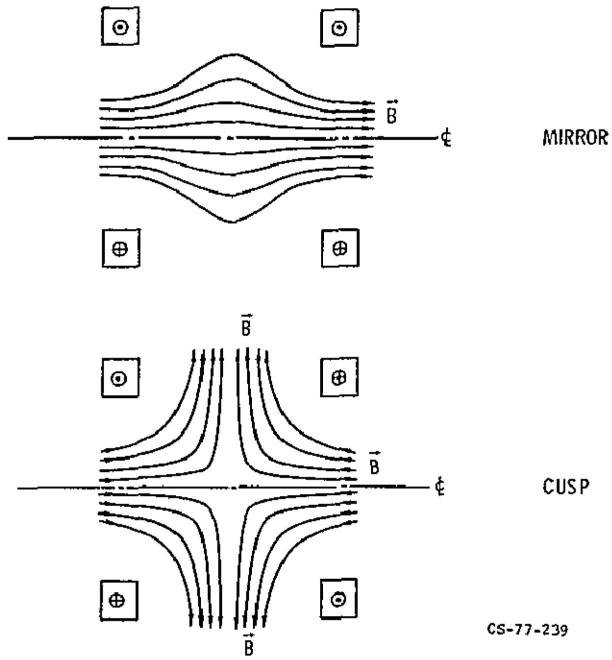
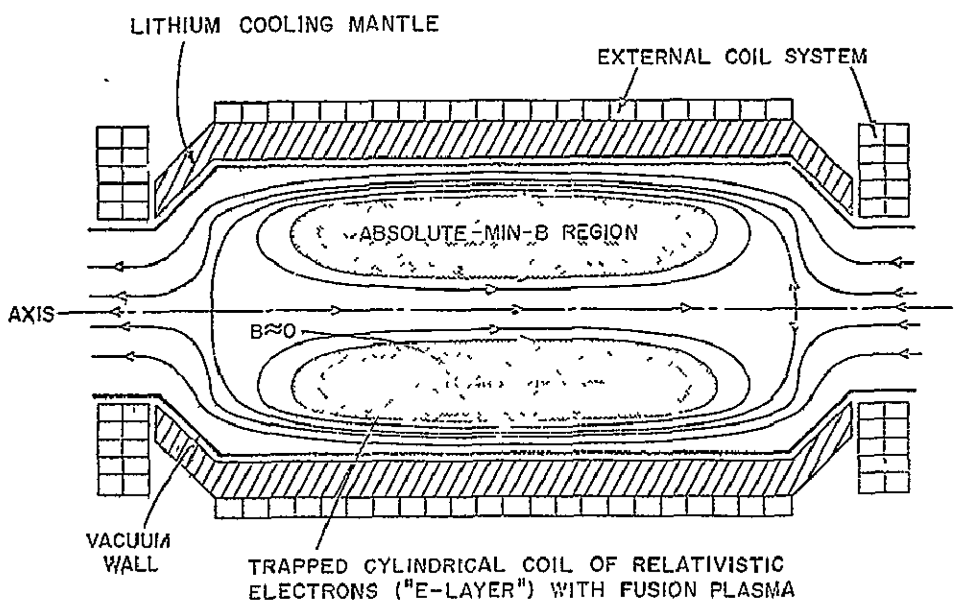


Figure 27



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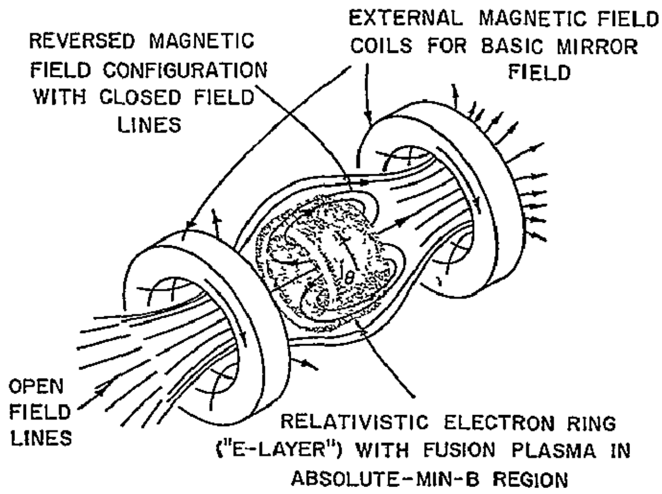

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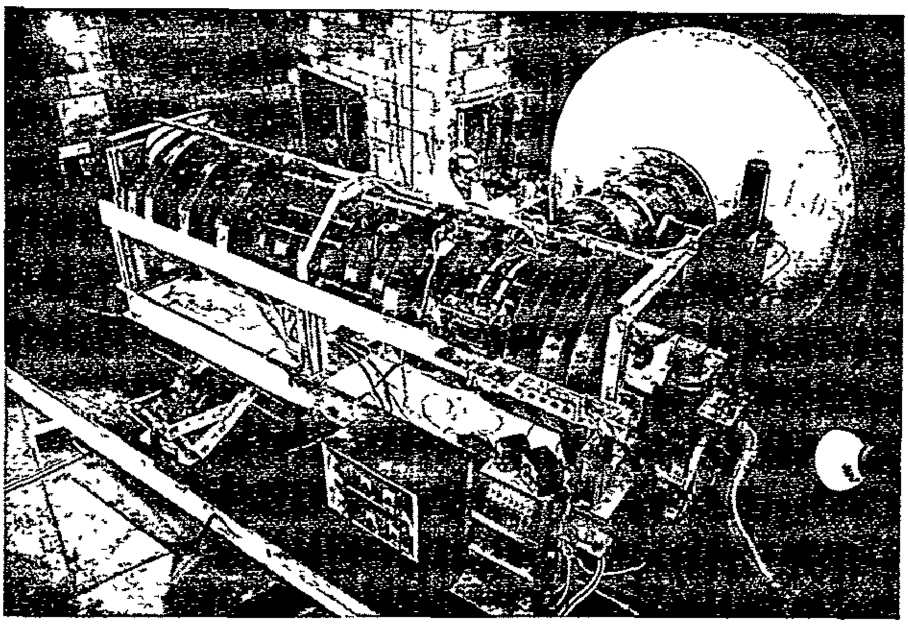

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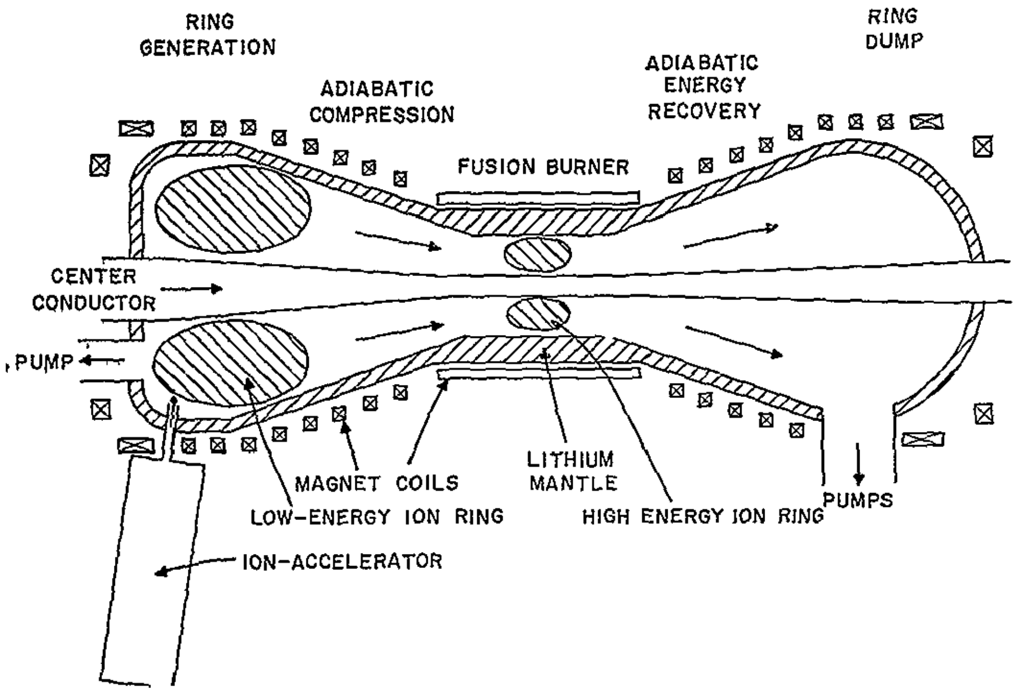

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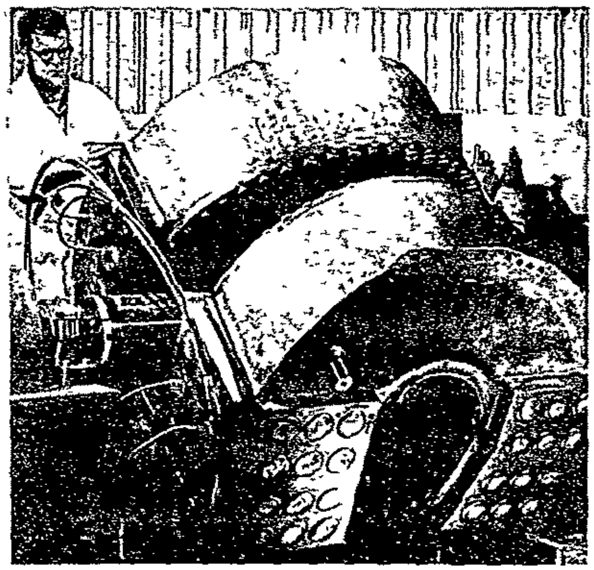


Figure 32.

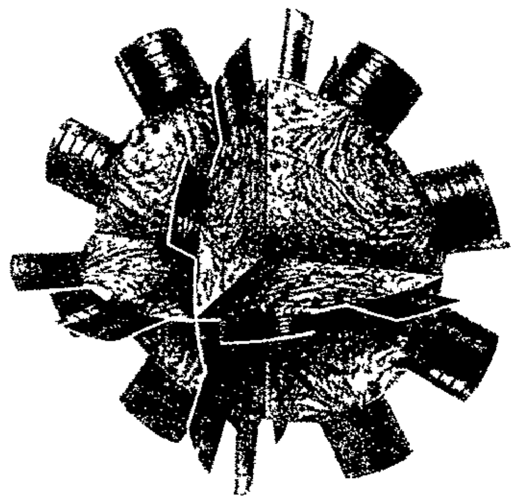


Figure 33.

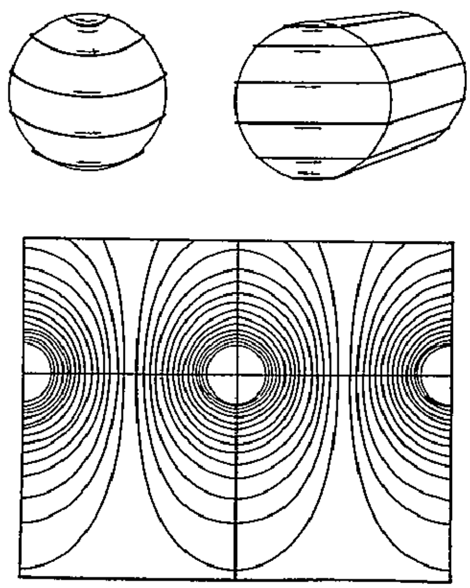


Figure 34

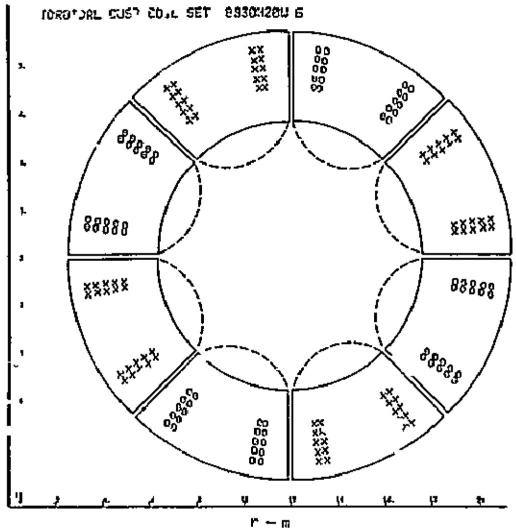


Figure 35.

E-9361

THE BUMPY TORUS CONCEPT

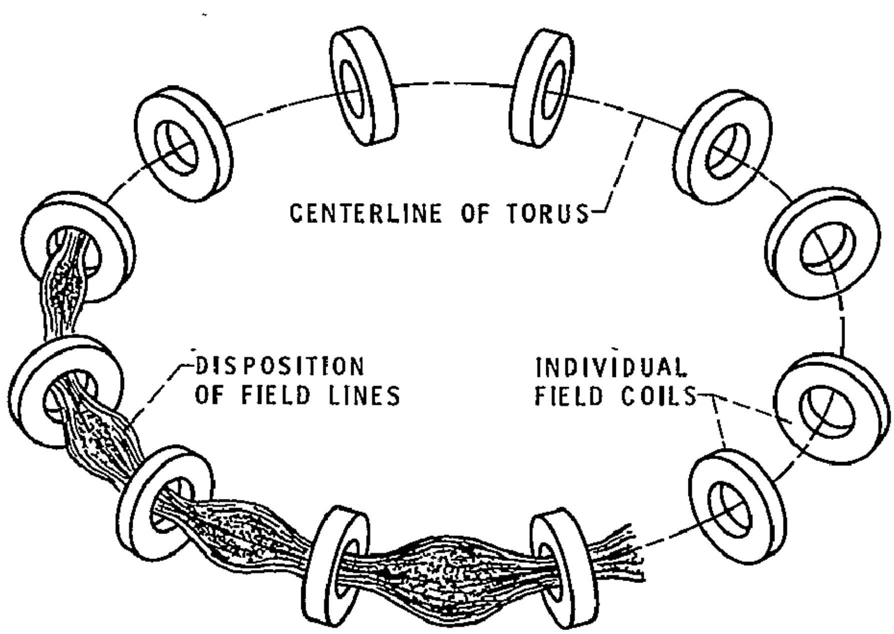
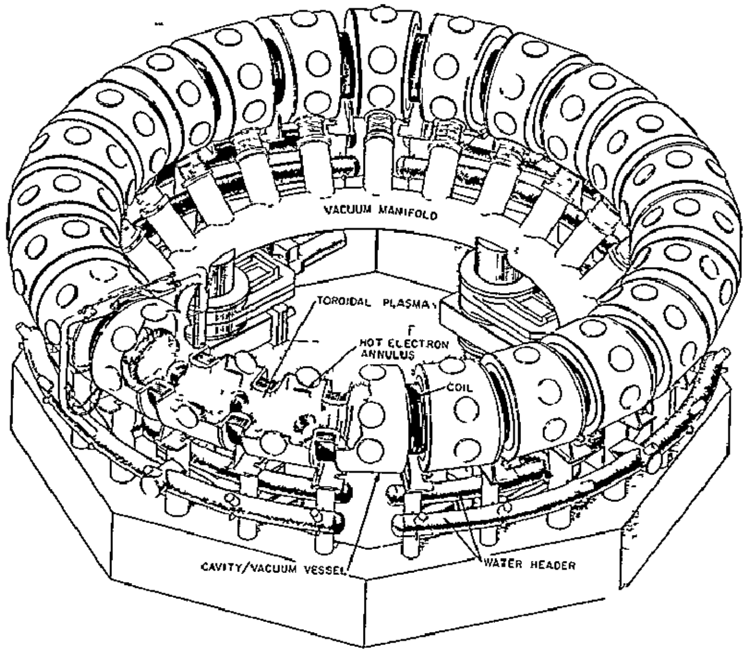


Figure 36.



ELMO Bumpy Torus

Figure 37

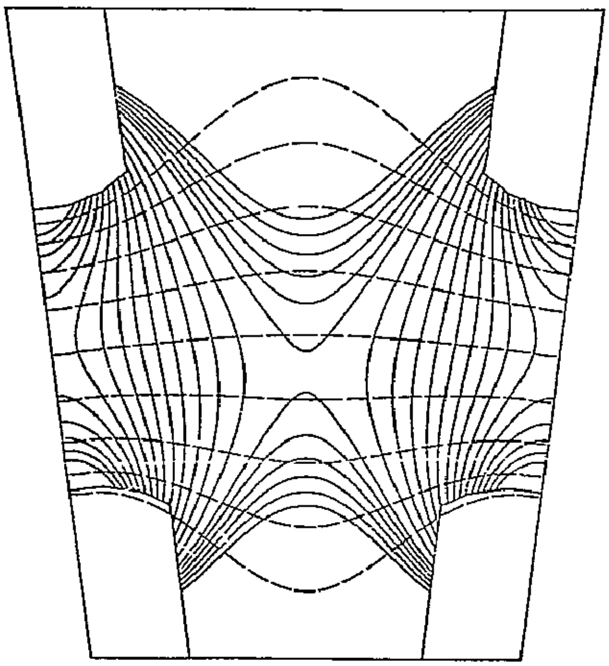


Figure 38

E-9361

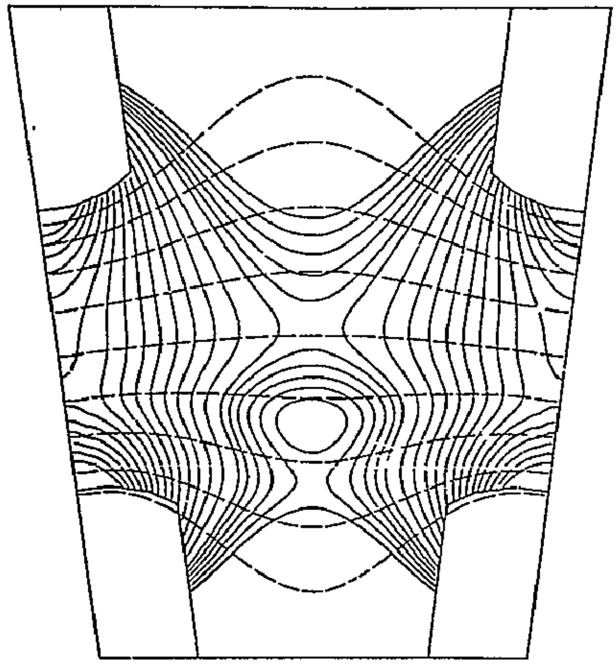
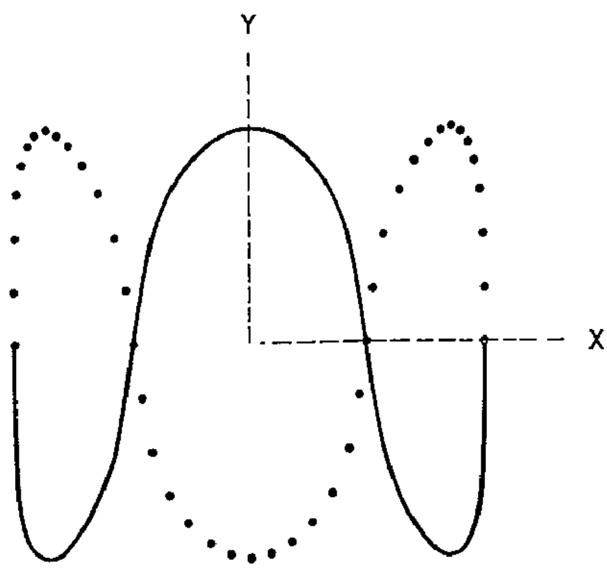


Figure 39



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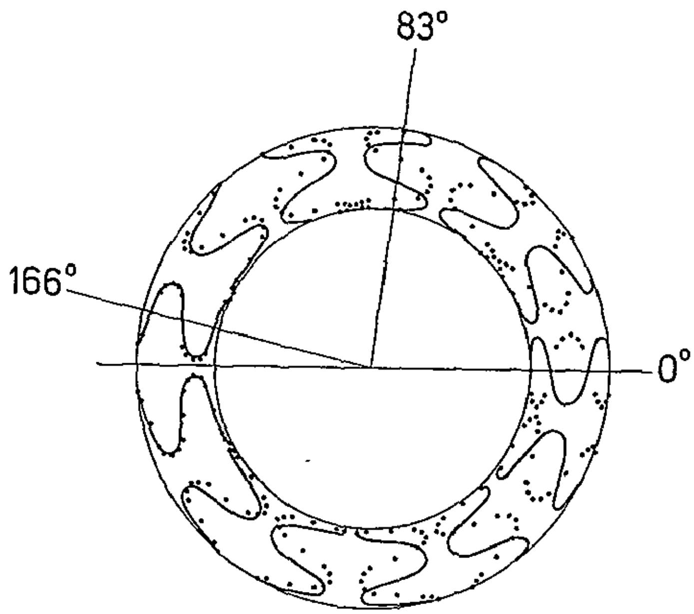

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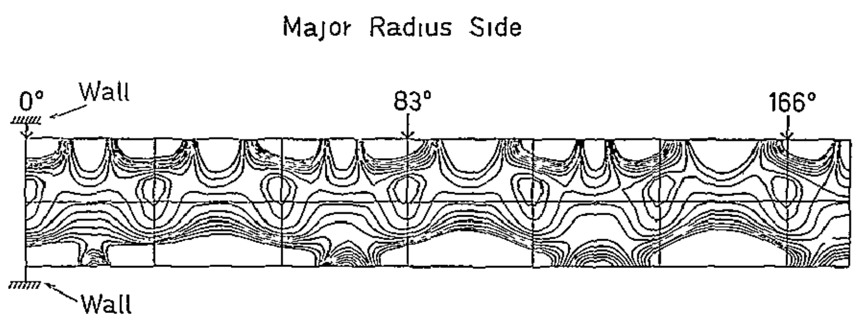


Figure 42

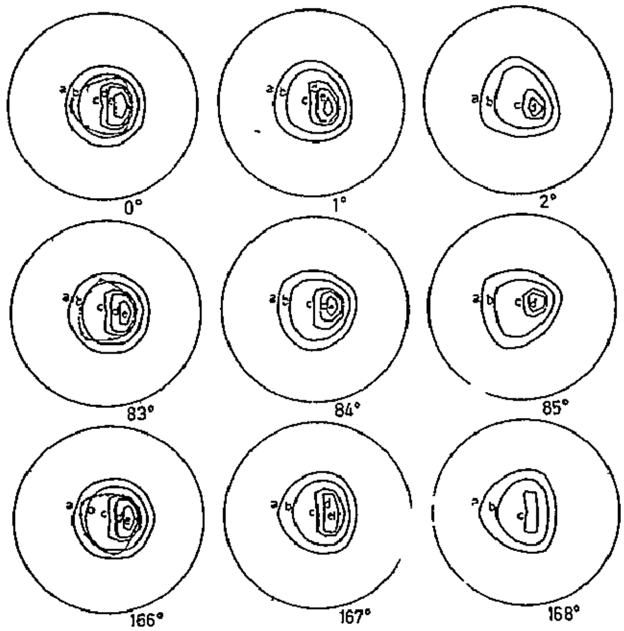
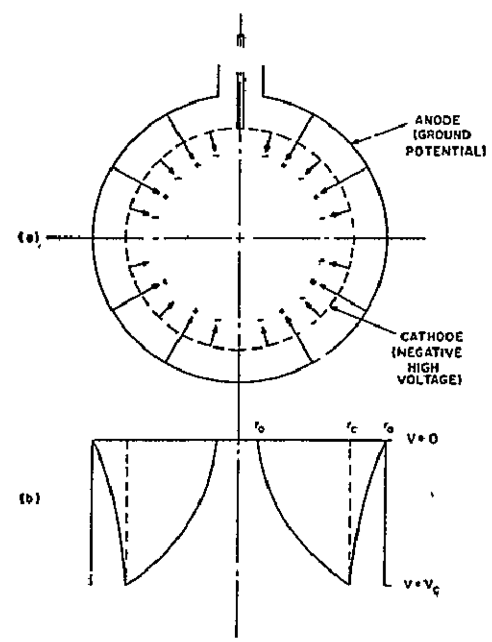


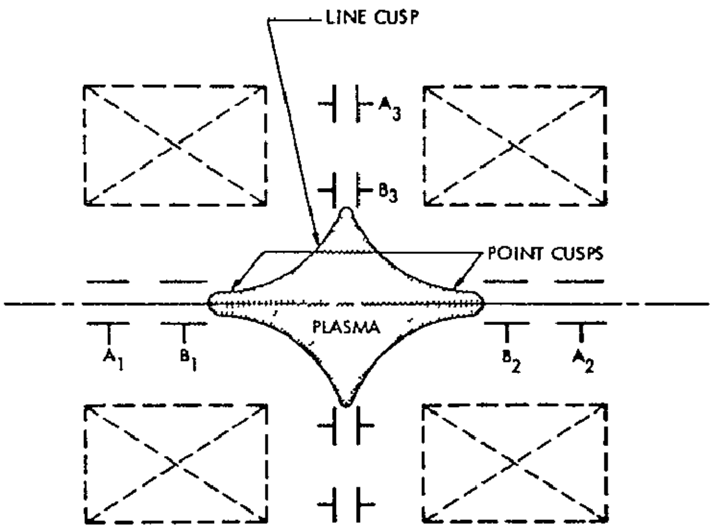
Figure 43.

E-9361



The general arrangement and the potential distribution when ions only are present

Figure 44



Cusp containment system with electrostatic electrodes

Figure 45

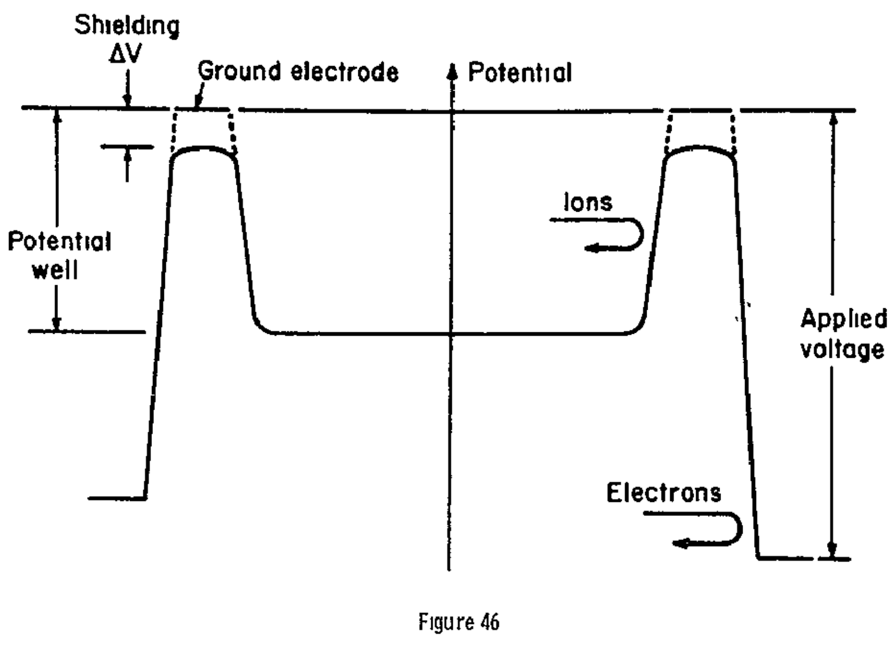


Figure 46

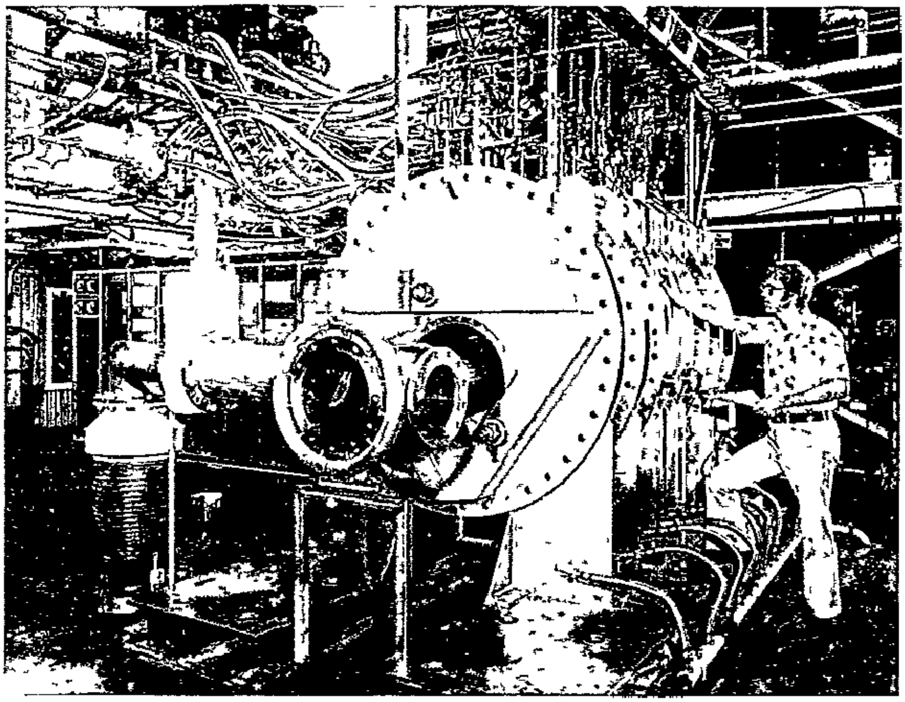
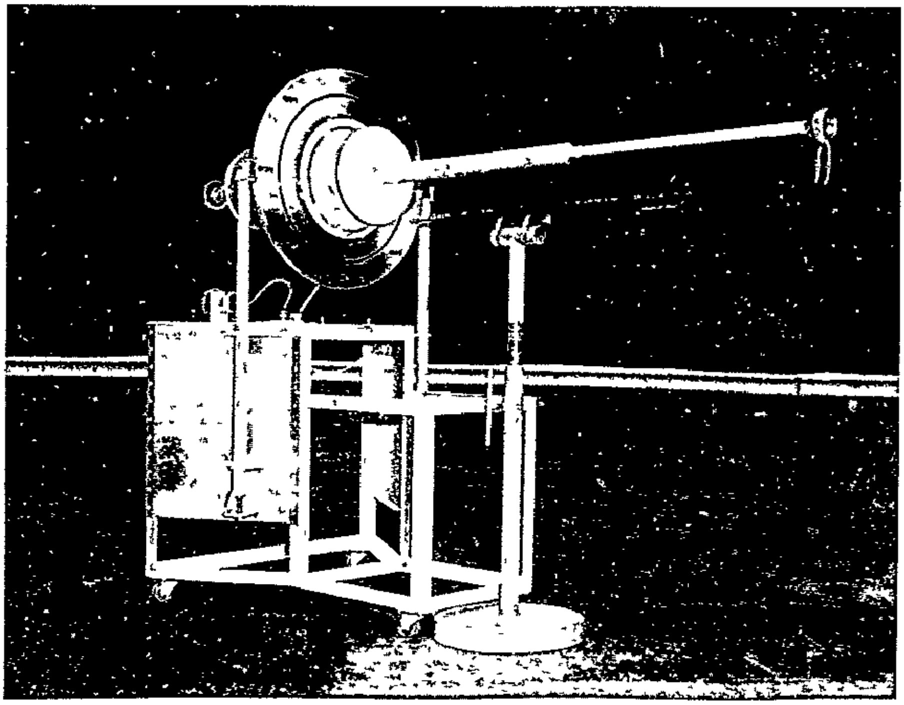


Figure 47

E-9361



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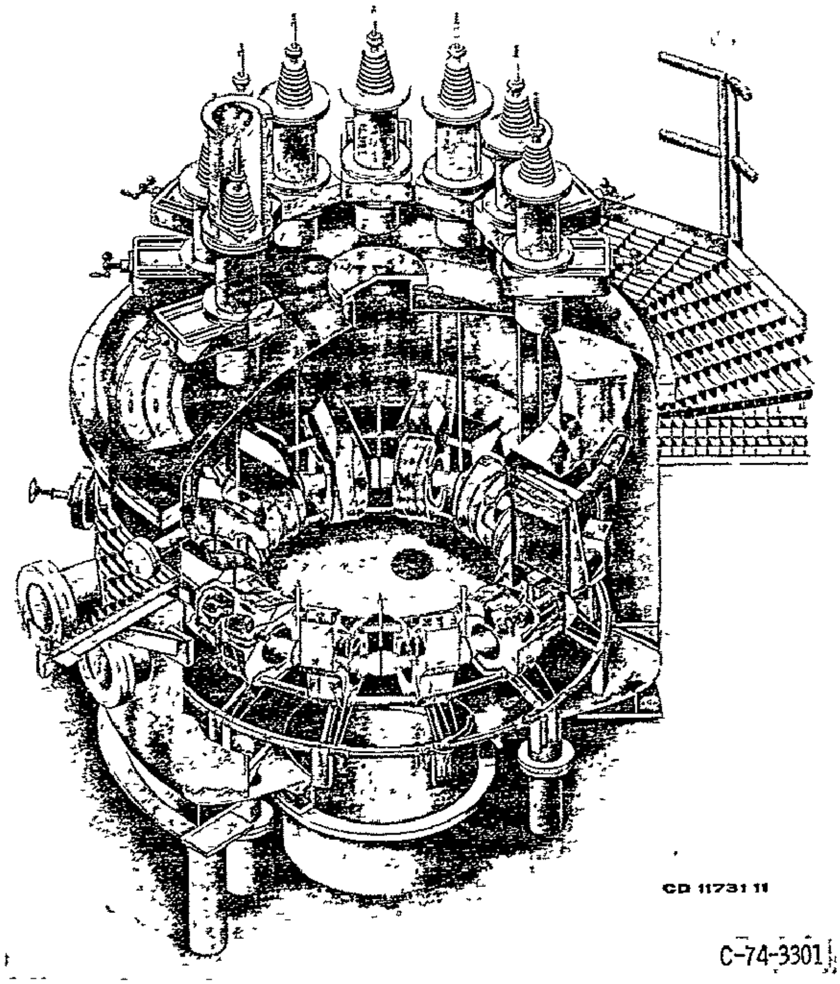


Figure 49 - Bumpy torus superconducting magnet facility.

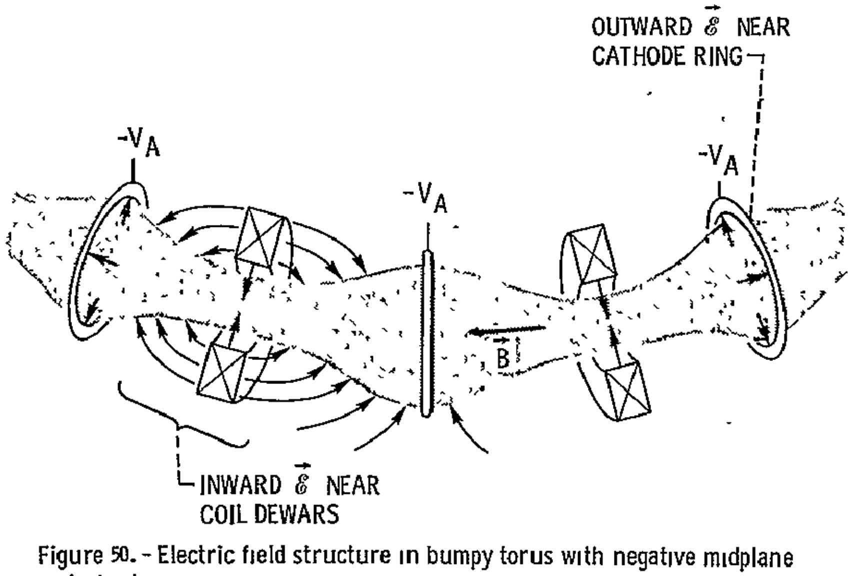
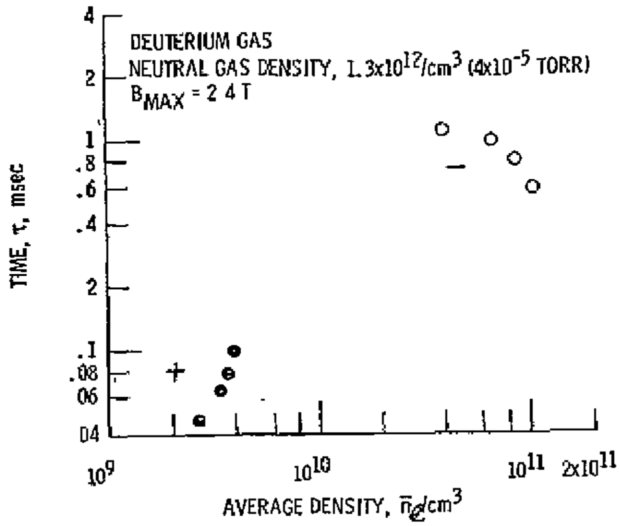


Figure 50. - Electric field structure in bumpy torus with negative midplane electrodes.

E-9361



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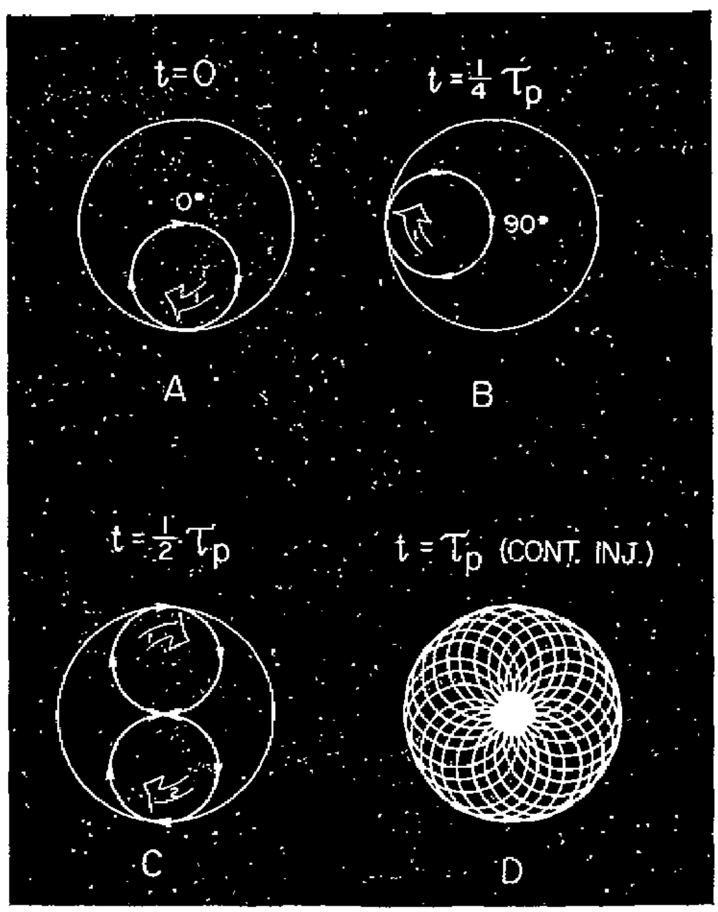

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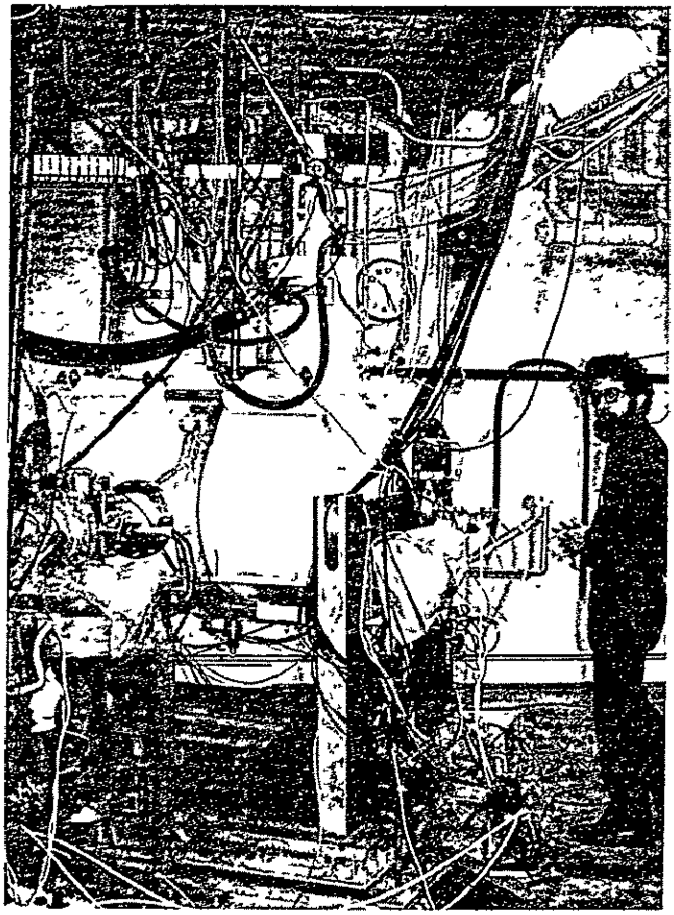

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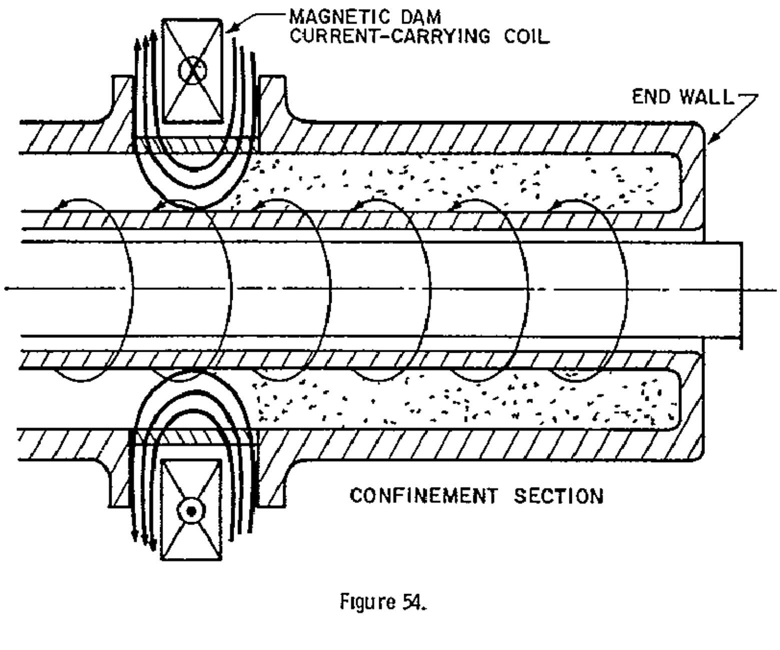

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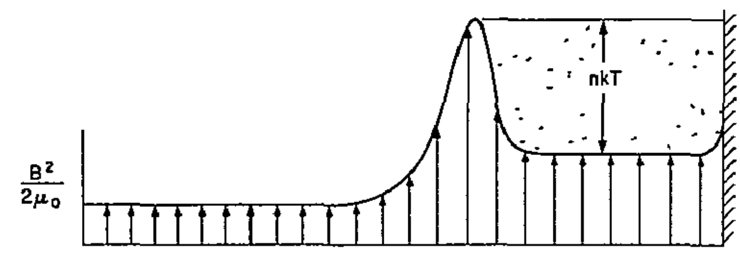

Figure 55

E-9361

LAWSON DIAGRAM OF ALTERNATIVE APPROACHES

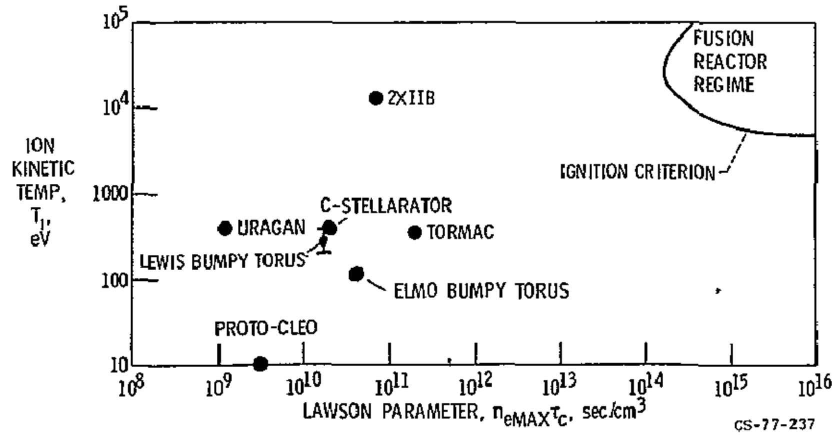

Figure 56

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