NASA TECHNICAL MEMORANDUM

NASA TM X-73429

NASA TM X-73429

(NASA-TM-X-73429) ALTERNATIVE APPROACHES TO FUSION (NASA) 54 p HC $4.50 CSCL 20I

N76-23999

Unclas
G3/75 28145

ALTERNATIVE APPROACHES TO FUSION

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

Invited lecture for a course on controlled fusion sponsored
by the IEEE Nuclear and Plasma Sciences Society
Austin, Texas, May 26-28, 1976

INTRODUCTION

The scope of this lecture is restricted to magnetic confinement concepts which may provide back-up or second-generation alternatives for the Tokamak fusion reactor, and which have been reduced to practice in the form of operating experimental apparatus. The Tokamak concept has been covered in previous lectures. The principal alternatives to Tokamak, theta pinches, open-ended geometries, and their modifications, will be covered in other lectures in this series. Inertial confinement schemes based on fusion microbombs which are ignited by irradiating fuel pellets with lasers or relativistic particle beams will also be covered in other lectures, as will the laser light pipe concept.

The purpose of this lecture is to describe alternative plasma confinement schemes in such a way that the basic principles of each device can be understood and associated with its name. Desirable characteristics of an advanced fusion reactor will be presented, and the present Tokamak reactor conceptual designs will be examined in light of these criteria.

Fusion reactions occur only at kinetic temperatures measured in tens of millions of degrees Kelvin. There are two recognized ways in which fusion reactions can be confined in the steady state, each employing a different field of force for confinement. The first possibility is the use of gravitational fields. This is known to work, because the sun and all the stars derive their energy from fusion reactions in their cores. This approach is infeasible in the laboratory because one must assemble in one place an amount of hydrogen somewhat larger than the planet Jupiter in order to ignite fusion reactions. The second method involves confinement of the energetic thermonuclear plasma by magnetic fields. This method is utilized in all of the concepts which will be discussed in this lecture.

When the energetic ions which form the fusionable fuel of a fusion reactor are confined in a strong uniform magnetic field, their trajectories are helices, as illustrated on the bottom of figure 1. When looked at along the magnetic field lines, the projected trajectories are circles with a characteristic radius of gyration which depends on the particle energy and the magnetic field strength. The particles are trapped on these magnetic field lines as long as they suffer no collisions. When collisions occur, the particles perform a slow random walk toward the walls of the containment vessel, with a step size equal to the particle gyroradius. This particle transport process is referred to as 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.

The limit to pure magnetic confinement imposed by classical diffusion is an important determining factor for the break-even power output of a fusion reactor. If it were possible to reduce the radial diffusion of plasma to values slower than that predicted by classical diffusion, the break-even power output of fusion reactors might become on the order of a few megawatts, small enough to be used on mobile vehicles. One possibility for improving steady-state plasma confinement beyond the classical limit is the simultaneous use of both electric and magnetic fields. In this approach, the already adequate confinement properties of a suitable magnetic field might be enhanced further by the judicious application of a strong electric field to the plasma.

Progress made in the magnetic containment of plasmas in toroidal devices is indicated on figure 2, which was taken from the report by Eastland and Gough (WASH 1132). 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. The confinement times remained constant at the Bohm value for nearly 10 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, as you heard in previous lectures. On figure 3 is shown the Lawson diagram, which plots the ion energy on the ordinate and the product of density and containment time on the abscissa. The regions appropriate to prototype fusion reactors and fusion power plants are indicated very schematically by the cross-hatched regions in the upper right. There has been steady progress toward the fusion reactor regime, with the Alcator experiment at MIT, a Tokamak device, currently in the lead. All the devices closest to the fusion reactor regime are Tokamaks, with the exception of the theta pinches under investigation at Los Alamos.

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. It is the current consensus that, unless unforeseen difficulties arise, the first demonstration fusion power plants will be DT Tokamak devices.

DESIRABLE CHARACTERISTICS OF A FUSION REACTOR

The characteristics of an ideal fusion reactor depend upon the ultimate application. A fusion reactor intended for the electric utilities will not necessarily be suitable for space or military applications or for commercial applications other than electrical power generation. The utilities desire a reactor which has minimum capital costs and cost of electricity, minimal environmental intrusion, and high reliability and availability. Space applications require a minimum total mass for a given power output, high 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. Military applications require mobility, reliability, and invulnerability.

In order to provide criteria by which fusion reactor concepts can be judged, it is useful to specify characteristics which a fusion reactor should have. Such a list is given in Table 1.

TABLE 1

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

Not all of these characteristics are necessarily desirable for all possible applications of fusion reactors, but they do imply increased attractiveness of fusion power for at least one of the possible areas of application.

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 with large or expensive external equipment prior to injection.

A fusion reactor should be capable of operating with advanced 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 reaction 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 some 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 at least minimize the neutron generation and/or activation of the reactor structure.

Many of these desirable characteristics of a fusion reactor are motivated by the criterion that a fusion power plant have the highest possible captial and resource productivity. It is becoming clear that both capital and natural resources are the principal limits on economic growth. Design studies have shown that fusion power plants based on the Tokamak concept may be just competitive, in terms of cost of electricity, with fission power plants (ref. 1). Such power plants would provide the world with electricity using a very plentiful natural resource. However, in a world experiencing increasing shortages, it would be desirable if less capital and natural resources were required to construct these plants.

It appears that only by exploiting fusion reactor concepts more advanced than those described in ref. 1 can one reverse the trend of declining capital and resource productivity.

LIMITATIONS OF THE TOKAMAK CONCEPT

When measured against the criteria just discussed, the present Tokamak fusion reactor conceptual designs are seen to have limitations in several areas. These are listed in Table II.

TABLE II

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 confines 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. If the down time required for purging and restart is comparable to the steam plant time constant, the 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 generally require higher kinetic temperatures, and a constant, 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 (ref. 1).

PRINCIPAL ALTERNATIVES TO TOKAMAK

At present, ERDA is concentrating its developmental effort on the Tokamak concept. It is hoped to have a scientific feasibility demonstration by the early 1980's and a demonstration fusion power plant by 1995. Should unforeseen difficulties cause the Tokamak concept to falter, there are a number of alternatives in the U.S. program. Except for the laser fusion effort, these are being funded at levels about 1/10 to 1/100 that of the Tokamak effort. The two alternative approaches receiving the highest funding (Scyllac theta pinch and the mirror machines) date back to the origins of fusion research in the early 1950's (ref. 2).

The Scyllac θ-pinch is under investigation at Los Alamos. This approach initially utilized linear θ pinches consisting of an evacuated confinement volume surrounded by a single turn coil, and this coil was energized by capacitor banks. This approach was the first to produce plasmas of densities and temperatures sufficiently high to yield thermonuclear neutrons, in 1958. By the mid-1960's, it became evident that end losses from linear theta pinches were large. To make further significant progress on the Lawson diagram, the theta pinch was modified into a toroidal geometry called Scyllac. A photograph of a 120° sector of the toroidal Scyllac facility is shown on figure 5. The evacuated chamber which contains the plasma is located in the circular sector near the technician on the right center of the photograph. The capacitor banks are to the left. Figure 6 shows data taken in a linear θ-pinch at Los Alamos (private communication) in which the dark fringes represent isodensity contours of the plasma. The uniformity of these contours illustrates the stable, quiescent containment of the compressed plasma.

The mirror alternative is being studied at the Lawrence Livermore Laboratory via attempts to confine a plasma in a minimum-B open-ended geometry, and at the NASA Lewis Research Center in DC heating experiments in a simple high field strength superconducting magnetic mirror called the SUMMA facility. The early work on the mirror approach to controlled fusion also dates from the early 1950's (ref. 2). At present, there are two major open-ended-experiments at the Livermore Laboratory; the 2xII device and the Baseball experiment. More will be said about the 2xII experiment in other lectures in this series. A photograph of the Baseball machine is shown on figure 7. The Baseball machine is so-called because the magnetic field windings are in the form of a baseball seam with a major diameter of approximately one meter. The windings shown in figure 7 are superconducting and produce a minimum B region of containment near the center of the windings. The magnetic field lines are not closed on themselves in the confinement volume and spread out in two fan-shaped loss regions from opposite lobes of the baseball. On figure 8 is shown a photograph of the dewar in which the baseball windings are located. This dewar is slightly to the left of center of the photograph with a liquid helium refrigerator located to the right. This facility and NASA's SUMMA facility are presently the two largest superconducting fusion facilities in the world.

Over the past 10 years, both the θ-pinch and open-ended approaches have made incremental advances in achieving higher plasma densities, containment times, and ion temperatures; but neither is as close in terms of $n\tau$ to the fusion reactor regime as the Tokamak. As one can see from figure 3, the best results from the θ-pinch are about a factor of five in $n\tau$ below the latest Alcator results and were achieved many years ago. The most recent results from the 2xII experiment are more than two orders of magnitude below the Alcator experiment in $n\tau$, although the ion kinetic temperatures are higher by about a factor of ten.

Design studies of hypothetical fusion power plants based on the θ-pinch or mirror machines have not been encouraging. The basic difficulty with both concepts is that a relatively large amount of recirculating power will be required, since there appears to be no way that the fusion reaction in such devices could be self-sustaining. The θ-pinch concept requires that the energy necessary to compress the plasma be recovered and stored between the compression pulses (ref. 3). In present experiments, this energy storage is provided by a capacitor bank, and no attempt is made to recover the magnetic energy. Capacitors are too unreliable and too expensive to be used in a θ-pinch reactor, and almost the only alternative for energy storage is superconducting magnets. The capital investment required for energy storage in superconducting magnetic fields is as great or greater than that required for the magnetic field coils in a Tokamak reactor (see ref. 3,for example).

The open-ended geometries are burdened by particle losses so high that, in order to produce net power, such a reactor must be capable of extracting energy from the charged particle efflux with high efficiency, and then reconverting this energy into energetic particles in the plasma. This recirculating power may typically be greater than the net power output of the plant. In a toroidal device, this recirculation of power occurs within the plasma and is represented by the transport of energetic charged particles from one point of the toroidal plasma to another. The open-ended geometries may have a role to play in fusion reactor development as power consuming fusion engineering test facilities, where fusion-like plasmas are generated for physics and engineering studies.

ADVANCED FUSION REACTOR CONCEPTS USING MAGNETIC CONTAINMENT

Over the past 5 years, it has become increasingly clear that if one wishes to improve upon the capital and resource productivity of the Tokamak reactor, one may need to exploit advanced fusion reactor concepts. The devices discussed below each appear to improve upon one or more of the limitations of the present Tokamak fusion reactor designs. Because these concepts are in an early stage of investigation, all of their limitations and advantages are not well defined. Therefore it is not possible at this time to evaluate whether, if pursued, they may provide viable alternatives to the Tokamak reactor. Some of the advantages and disadvantages of the concepts discussed below are summarized in Table III at the end of the text.

Tormac

The Tormac confinement concept has been developed by M. A. Levine and his colleagues (refs. 4-8). The current-carrying conductors of the Tormac concept are shown in figure 9. 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 of 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 (refs. 7 and 8) 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 10. 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. Like the Tokamak, the plasma contains strong toroidal currents which help to confine the plasma, so the Tormac is basically a cyclic plasma containment concept. If the Tormac could be developed to a fusion reactor, it may have the advantages and disadvantages listed in column 1 of Table III.

Topolotron

The Topolotron concept has been developed by R. W. Bass, J. H. Gardner, et al. (refs. 9-11) at Brigham Young University in Provo, Utah. The basic Topolotron configuration is shown in figure 11, 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 9 and 11 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 are in the poloidal direction, like the theta pinch, while they flow in the toroidal direction in the Tormac.

The Topolotron has a further interesting property illustrated in figure 12. 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 13. On figure 14 is shown a photograph of the Topolotron apparatus in a partially assembled state. It is hoped to perform experiments on the Topolotron in mid or late 1976. If the Topolotron concept could be scaled up to a fusion reactor, its advantages and disadvantages relative to the Tokamak would be similar to those of the Tormac and are listed in column 2 of Table III.

Stellarator

The Stellarator concept was originated in the U.S. at Princeton in 1952 (ref. 2), but has fallen into relative neglect in the United States since about 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 15 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 circumference. This leads to a stronger magnetic field along the inside radius of the plasma than along the outside radius, and 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 be lost 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 16. 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 17. The tightly wound helix represents the 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. This is illustrated in the lower-right-hand corner of figure 17. The magnetic field lines along the plasma column rotate around the axis far more on the outside than on the inside. 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.

The behavior of the magnetic field lines in a stellarator geometry is illustrated in figures 18 and 19, two views of a L = 3 stellarator, in which six helical windings containing three pairs of oppositely flowing currents are on the outside; and the magnetic field lines with their shear and varying degrees of rotational transform are in the plasma volume.

A plot of the magnetic field strength contours and the particle drift surfaces are shown in figure 20 for an L = 3 stellarator such as the one Proto-Cleo device at the University of Wisconsin (ref. 12). On figure 21 is shown an experimental determination of the drift surfaces of an L = 3 stellarator in which 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 the radius.

A schematic diagram of one of the early stellarator experiments at Princeton University is shown on figure 22. These stellarators were built in a racetrack configuration in which only the curved end portions had a helical winding. The toroidal coils, the helical stellarator windings, the ohmic heating coils, the divertor, and two straight sections of magnetic field are indicated. On figure 23 is a photograph of one of the early stellarators, which is about 1 meter by 2 meters long in a racetrack configuration. Outside the U.S., there currently are active stellarator research programs in Russia, West Germany, England, France, and Japan. In figure 24 is shown a photograph of the Russian L2 stellarator, which is symmetric without the straight sections used in the 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 25 (ref. 12).

The stellarator geometry has the important advantage over the Tokamak that all the currents which confine the plasma are external to the plasma. Unlike the Tokamak, the stellarator does not require currents flowing in the plasma to assist in confinement. For this reason, the stellarator can, in principle, 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. The potential advantages and disadvantages of the Stellarator with respect to the Tokamak are listed in column 3 of Table III.

Torsatron

The torsatron concept is under investigation by Hamberger and Sharp (ref. 14) at the Culham Laboratory in England. 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 conductor geometry is illustrated in figure 26, which is a photograph of the torsatron windings in use at the Culham Laboratory. 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, and the drift surfaces in 5 degree increments along one of these sectors are shown in figure 27. The windings shown in figure 26 are contained in a large vacuum tank, a sketch of which is shown in figure 28. A photograph of the torsatron plasma was taken through one of the top viewports of this vacuum tank and is shown in figure 29.

An examination of figures 26 and 29 makes obvious the basic simplicity of the torsatron magnetic field windings, and this is very significant from an engineering point of view. The torsatron has a further interesting property which, as it happens, is not exemplified by this particular experiment. In figure 26 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. This potentially represents a 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, and those which arise from a finite plasma beta relative to the force-free vacuum field configuration. The advantages and disadvantages of the torsatron configuration relative to the Tokamak are listed in column 4 of Table III.

Bumpy Torus

The pure bumpy torus is illustrated on figure 30 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 represent 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 bumpy torus magnetic field configuration was first investigated in this country by Gibson, Jordan, and Lauer (refs. 15 and 16) and is currently being pursued at the Oak Ridge National Laboratory (refs. 17 and 18). In the Elmo Bumpy Torus experiment at Oak Ridge, relativistic electrons are generated with microwaves and are trapped near the midplane of each sector to the extent that beta values exceeding .5 have been measured in steady-state operation. This provides encouraging experimental evidence that high beta plasmas can be confined in the bumpy torus configuration, at least when circulating relativistic electron currents are present. The geometry of the magnetic field windings is modular and extremely simple in the bumpy torus, implying an engineering advantage for this concept. The advantages and disadvantages of the bumpy torus relative to Tokamak are listed in column 5 of Table III.

Bumpy Torus with Electric Field

The bumpy torus approach under investigation at the NASA Lewis Research Center (refs. 19-26) is characterized by three factors:

1) the magnetic field and the plasma heating mechanism are operated in the steady state. 2) strong magnetic and electric 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 31. 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 32 shows a photograph of the Bumpy Torus plasma. 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 not given by the conventional "classical" or "Bohm" diffusion relationships. On figure 33 is data showing the average particle residence time as a function of magnetic field. The residence time is virtually independent of magnetic field over a factor of 10 variation in B. This independence of magnetic field would be very surprising if the plasma were confined by pure magnetic fields, since Bohm or classical confinement predict confinement times which vary as B or B^2, respectively.

The possible advantages and disadvantages of the electric field bumpy torus are shown on column 6 of Table III.

Astron and Reverse Field Devices

The astron concept was first proposed in the mid-1950's (ref. 2, 27) and consisted of a geometry similar to that shown in figure 34. 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 adjusted so their gyrodiameters are comparable to the diameter of the intended plasma confinement region. The relativistic particles are caused to build up to such a point that the diamagnetic field generated by their motion exceeds that of the applied magnetic field. At this point, the magnetic field will reverse inside the layer of gyrating relativistic particles, and closed magnetic field lines will encircle the ring of gyrating particles. 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 built up its relativistic e-layer to more than about 15% of magnetic field reversal. Subsequent experiments by Fleischmann and others at Cornell University (ref. 28) have injected relativistic electrons into a pulsed mirror magnetic field and achieved a field reversal in this geometry. The essence of their approach is indicated on figure 35, and a photograph of their experiment is shown in figure 36. 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 37.

Recent results from the 2xII experiment at Livermore indicate that the plasma in this device may also be producing a reverse-field configuration, with very low magnetic fields on the plasma axis, or possibly even field reversal. Once magnetic field reversal is achieved, it is hoped that the closed magnetic field lines will provide a plasma containment mechanism. 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 not only must assure the stability of the e-layer or p-layer. The external equipment required to generate the e-layer or p-layer may not be required in magnetic compression experiments similar to the 2xII, but one pays a penalty by not being able to run the device in the steady state. The advantages and disadvantages of the reverse-field devices with respect to the Tokamak are listed in column 7 of Table III.

The Migma Concept

The migma concept for controlled fusion represents a combination of two approaches: the colliding beam storage ring concept from high energy nuclear physics, and the energetic neutral injection concept from mirror machine research. This concept has been conceived and promoted by B. C. Maglich and his coworkers (refs. 31-33). The essence of this concept is illustrated on figure 38. Energetic neutrals are injected into a magnetic field and ionized in such a way that they gyrate in circles shown in figure A. These gyrating particles can be made to precess about the magnetic axis as is illustrated in figure B. Once a large number of particles are accumulated and gyrating around the magnetic axis, the situation illustrated in figures C 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 D. 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 as is illustrated in figure 39, 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. On figure 40 is shown a photograph of the chamber of the current migma experiment in which the particles are injected and trapped in the gyrating orbits. The superconducting magnets which produce the uniform field along the axis of this device is shown in figure 41.

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 also clear that the Migma concept, like the mirror-machine reactor, will require a large amount of circulating power to provide the energetic charged particles injected into the plasma. The generation of energetic charged particles with more than an MeV of energy, required for the Migma concept, may not be possible with high efficiency. The potential advantages and disadvantages of the Migma concept relative to the Tokamak are listed in column 8 of Table III.

SUMMARY

If it could be shown possible to generate electrical 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. Such a situation may be possible for advanced fuel cycle plants, and the possibility has already been shown to exist in the area of space propulsion.

For manned interplanetary missions and unmanned exploration of the outer planets, advanced fusion rockets may have outstanding capabilities. Studies have shown (ref. 34) that if advanced cycle fusion rockets (based on the D-He^3 reaction) could be built, they may have a specific mass (kilograms of power plant per kilowatt of rocket exhaust power) as low as 1/10 that of fission electric rockets. DT fusion reactors, however, would not have any advantage over fission reactors since either must operate with heat engine electric power cycles.

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. 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 feasibility alone will not be sufficient. Those of us in the fusion community must not only be able to guarantee the feasibility of controlled fusion, but we must be able to show that its capital and resource productivity, as well as its environmental acceptability, are at least as good as alternative energy sources. It is too early to state which, if any, of the advanced concepts described above will be feasible or will find their way into the mainstream of fusion research. Many of these concepts, however, have one or more attributes which make them a potential improvement over the Tokamak concept in terms of environmental acceptability and/or capital and resource productivity. If fusion reactors are going to be better as well as feasible, there must exist a climate in which the search for improved alternative concepts is cultivated.

ACKNOWLEDGEMENTS

The author would like to thank H. H. Fleischmann, J. H. Gardner, M. A. Harrison, M. A. Levine, R. A. Miller, L. E. Sharp, and J. L. Shohet; all of whom provided illustrations relating to their work.

REFERENCES

1. Mills, R. G., Editor: A Fusion Power Plant. MATT 1050, August 1974, pp. 521-22.

2. Bishop, A. S.: Project Sherwood. Addison-Wesley Publishing Company, Reading, MA (1958).

3. Thomassen, K. I., et al.: Conceptual Design Study of a Scyllac Fusion Test Reactor. Report LA-6024, January 1976.

4. Gallagher, C. C.; Combes, L. S.; and Levine, M. A.: Plasma Behavior in a Toroidal High-β Device. Phys. Fluids, Vol. 13, No. 6, pp. 1617-75 (1970).

5. Levine, M. A.; Boozer, A. H., Kalman, G.; and Bakshi, P.: Particle Loss in a Toroidally Symmetric Cusp. Phys. Rev. Letters, Vol. 28, 1323-26 (1972).

6. Boozer, A. H. and Levine, M. A.: Particle Trapping in Magnetic Line Cusps. Phys. Rev. Letters, Vol. 39, 1287-91 (1973).

7. Levine, Morton A.: The Tormac Containment Device for Fusion. Proc. 2nd IEEE Conf. on Plasma Science, May 14-16, 1975, 75CH0987-8-NPS, p. 60.

8. Brown, I. G.; Levine, M. A., and Myers, B. R.: Plasma Confinement in the Tormac V Device. APS Bulletin, Vol. 20, No. 10, October 1975, p. 1357.

9. Gardner, J. H., et al.: The Topolotron, A Device for the Magnetic Confinement of Plasmas. Proc. Utah Acad., Vol. 90, Pt. 2, 1973, pp. 1-11.

10. Brown, K. H.; Ferguson, H. R. P.; Gardner, J. H.; Knight, L. V.; and Nelson, H. M.: The Topolotron: A High Beta Device with Topological Stability. Proc. 2nd IEEE Conf. on Plasma Science; May 14-16, 1975; 75CH0987-8-NPS, p. 59.

11. Bass, R. W.; Ferguson, H. R. P.; Gardner, J. H.; Harrison, B. K.; and Larsen, K. M.: A Nonlinear Energy Principle with Applications to the Topolotron. APS Bulletin, Vol. 20, No. 10, October 1975, p. 1311.

12. Shohet, J. L.: Enhanced Transport in Non-Axisymmetric Toroidal Devices Due to Conversion of Trapped to Circulating Particles by Fluctuations. Proc. 2nd IEEE Conf. on Plasma Science; May 14-16, 1975, 75CH0987-8-NPS, p. 62.

13. Dellis, A. N.; Gill, R. D.; Lees, D. J.; Millar, W.; and Shatford, P. A.: Ohmic Heated Plasma in the Cleo Stellarator. APS Bulletin, Vol. 20, No. 10, October 1975, p. 1337.

14. Hamberger, S. M. and Sharp, L. E.: Heating and Confinement in an Ultimate Torsatron. APS Bulletin, Vol. 19, No. 9, October 1974, p. 906.

15. Gibson, G.; Jordan, W. C.; Lauer, E. J.: Bumpy Torus. Phys. Rev. Letters, Vol. 4, No. 5, pp. 217-19, March 1, 1960.

16. Gibson, G.; Jordan, W. C.; Lauer, E. J.; and Woods, C. H.: Guiding Center Motion and Plasma Behavior in the Bumpy Torus. Phys. Fluids, Vol. 7, No. 4, April 1964, pp. 548-56.

17. Dandl, R. A.: Studies of Plasma Confinement and Heating in the ELMO Bumpy Torus. APS Bulletin, Vol. 19, No. 9, October 1974, p. 906. See also ORNL TM-4941, June 1975.

18. Dandl, R. A.; et al.: Plasma Confinement and Heating in the ELMO Bumpy Torus (EBT). Paper IAEA-CN-33/B6 in Proc. of IAEA Fifth Conf. on Plasma Physics and Controlled Nuclear Fusion Research. Tokyo, Japan, Vol. II, pp. 141-149 (1975).

19. Gerdin, G. A. and Roth, J. R.: Ion Energy Distribution Functions in the NASA Lewis Bumpy Torus. APS Bulletin, Vol. 18, No. 10, 1973, p. 1353.

20. Richardson, R. W.: Spectroscopic Results from the NASA Lewis Bumpy Torus Plasma. IEEE Conf. Record 74CH0922-5-NPS, p. 33, May 1974.

21. Gerdin, G. A.: Radio Frequency Studies in the Lewis Bumpy Torus. IEEE Conf. Record, 74CH0922-5-NPS, p. 34, May 1974.

22. Gerdin, G. A.; Spoke Wavenumbers and Mode Transitions in the NASA Lewis Bumpy Torus. APS Bulletin, Vol. 19, No. 9, 1974, p. 906.

23. Richardson, R. W.: Effect of Anode Ring Arrangement on the Spectroscopic Characteristics of the NASA Lewis Bumpy Torus Plasma. APS Bulletin, Vol. 19, No. 9, 1975, p. 906.

24. Richardson, R. W.: Determination of Electron Temperature in a Penning Discharge by the Helium Line Ratio Method. NASA TM X-71677, May 1975.

25. Gerdin, G. A.: RF Diagnostics on the NASA Lewis Bumpy Torus. IEEE Conf. Record, 75CH0987-8-NPS, p. 61, May 1975.

26. Roth, J. R.; Gerdin, G. A.; and Richardson, R. W.: Characteristics of the NASA Lewis Bumpy Torus Plasma Generated with Positive Applied Potentials. NASA TN D-8114, March 1976.

27. Briggs, R. J., et al.: Astron Program Final Report. UCRL-51874, Aug. 1975.

28. Phelps, D. A.; Smith, A. C., Jr.; Woodall, D. M.; Meger, R. A.; and Fleischmann, H. H.: Observations of the Stable Equilibrium and Classical Diffusion of Field Reversing Relativistic Electron Coils. Physics of Fluids, Vol. 17, No. 12, December 1974, pp. 2226-35.

29. Humphries, Stanley, Jr.: Prospects for the Use of Proton Rings for Plasma Confinement. Proc. 2nd IEEE Conf. on Plasma Science; May 14-16, 1975; 75CH0987-8-NPS; p. 63.

30. Fleischmann, H. H. and Kammash, T.: System Analysis of the Ion Ring Compressor Approach to Fusion. Nuclear Fusion, Vol. 15, (1975), pp. 1143-55.

31. Maglich, B. C.; Blewett, J. P.; Colleraine, A. P.; and Harrison, W. C.: Fusion Reactions in Self-Colliding Orbits. PRL, Vol. 27, No. 14, October 4, 1971, pp. 909-12.

32. Mazarakis, M.; Nering, J.; Maglich, B.; Rago, C.; Sandberg, J.; Powell, C.; Miller, R. A.; Channon, S.; Adler, E. A.; and Marcus, P.: High Energy Migma System at Fusion Energy Institute. APS Bulletin, Vol. 19, No. 9, October 1974, p. 913.

33. Maglich, B.; Channon, S.; Mazarakis, M.; Menasian, S.; Miller, R. A.; Nering, J.; Powell, C.; Sandberg, J.; Treglio, J.; and Whittemore, T.: Design Study of 100 kW ^3He-^3He Prototype Migma Fusion Power Plant. APS Bulletin, Vol. 20, No. 10, October 1975, p. 1316.

34. Roth. J. R.; Rayle, W. D.; and Reinmann, J. J.: Technological Problems Anticipated in the Application of Fusion Reactors to Space Propulsion and Power Generation. NASA TM X-2106. October 1970.

TABLE III

RELATIVE MERITS OF ADVANCED FUSION REACTOR CONCEPTS

ADVANTAGES	TORMAC	TOPOLOTRON	STELLARATOR	TORSATRON	BUMPY TORUS	ELECTRIC FIELD BUMPY TORUS	REVERSE FIELD DEVICES	MIGMA
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 LEAKAGE	✓	✓						
COMPLEX MAGNETIC COILS	✓	✓	✓					
COSTLY PLASMA HEATING EQUIPMENT					✓		✓	✓

E-8772

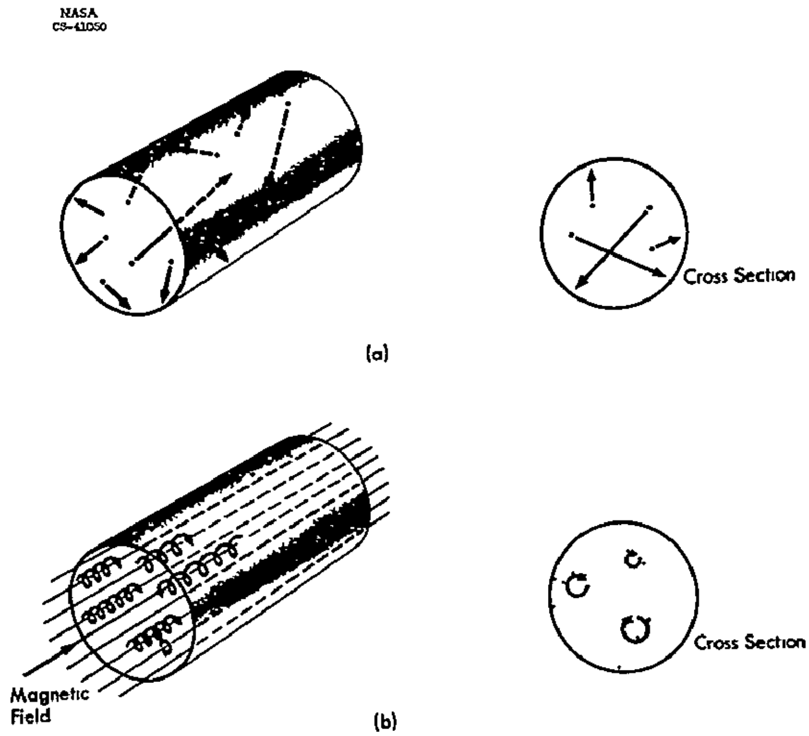


FIGURE 1

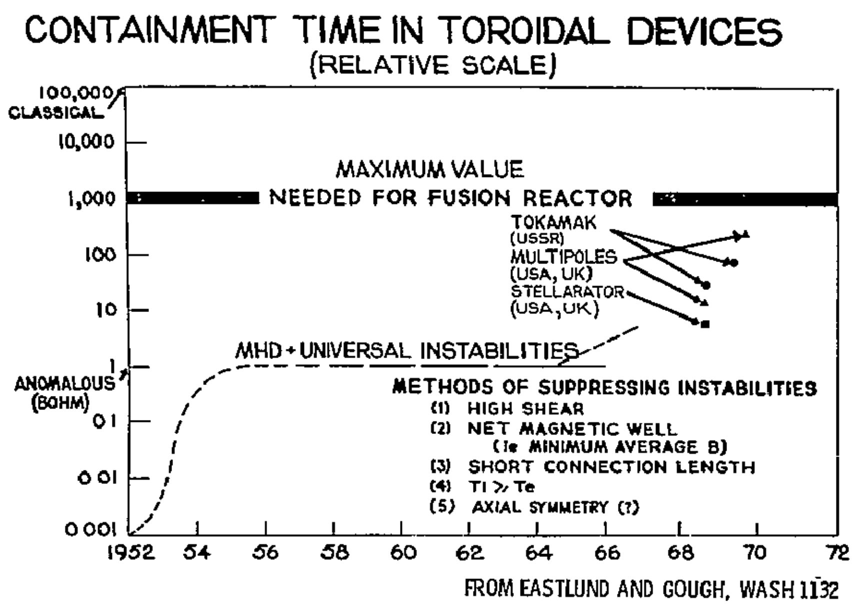


FIGURE 2

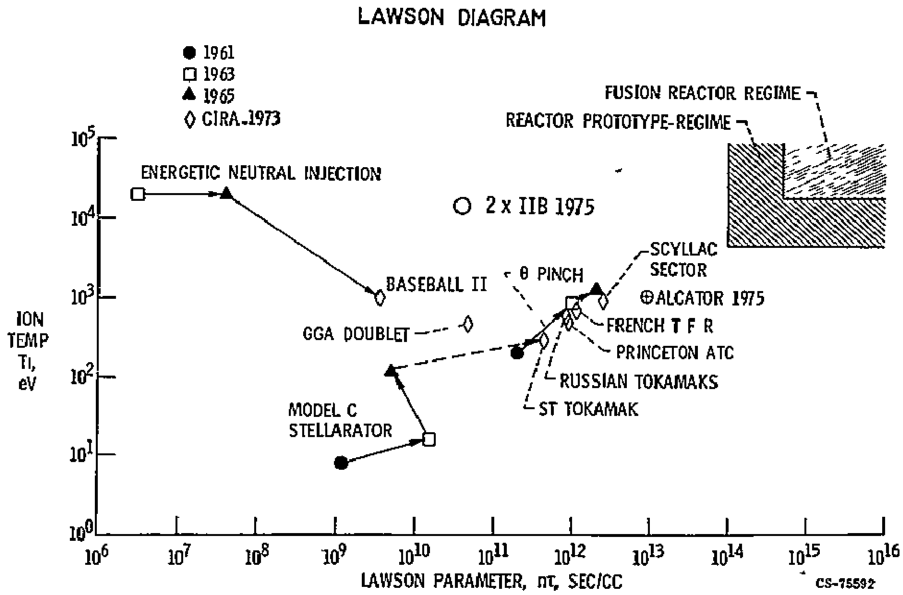


FIGURE 3

SHORTCOMINGS OF TOKAMAK REACTOR CONCEPT

1 CANNOT OPERATE IN STEADY STATE

2 LOW PLASMA ENERGY DENSITY REQUIRED FOR STABILITY

3 ADVANCED FUSION FUEL CYCLES APPEAR INFEASIBLE

4 FUSION REACTION PROBABLY NOT SELF-SUSTAINING

5 HIGH CAPITAL INVESTMENT IN MAGNETIC FIELD COILS, PLASMA HEATING EQUIPMENT

6 DIVERSION & CONTROL OF PARTICLE EFFLUX A PROBLEM

CS-75578

FIGURE 4

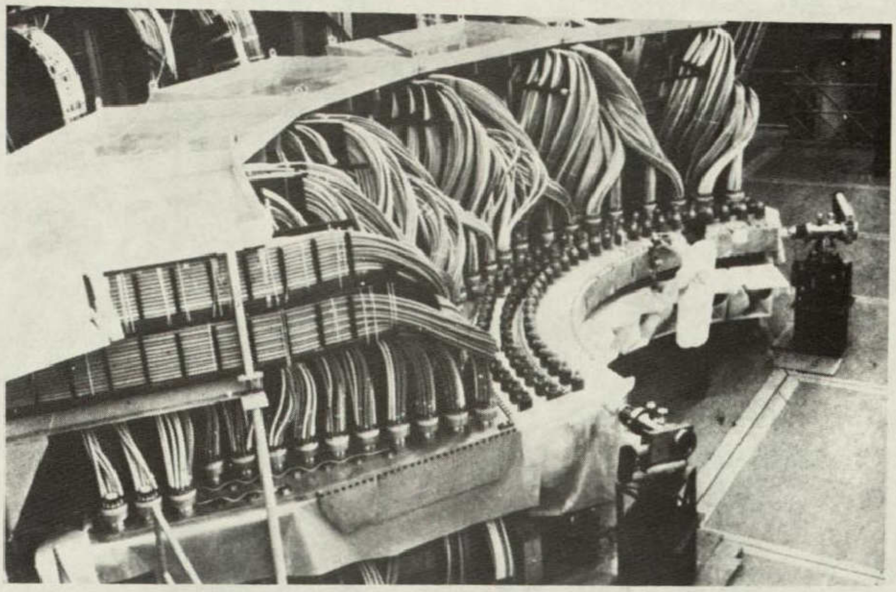


Fig. II-4.
Photograph of the front end of the toroidal sector.

FIGURE 5

E-8772

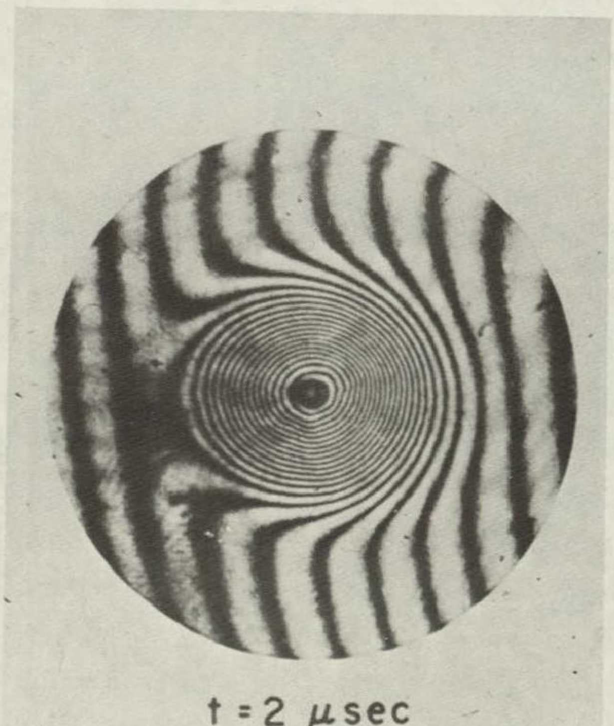


FIGURE 6

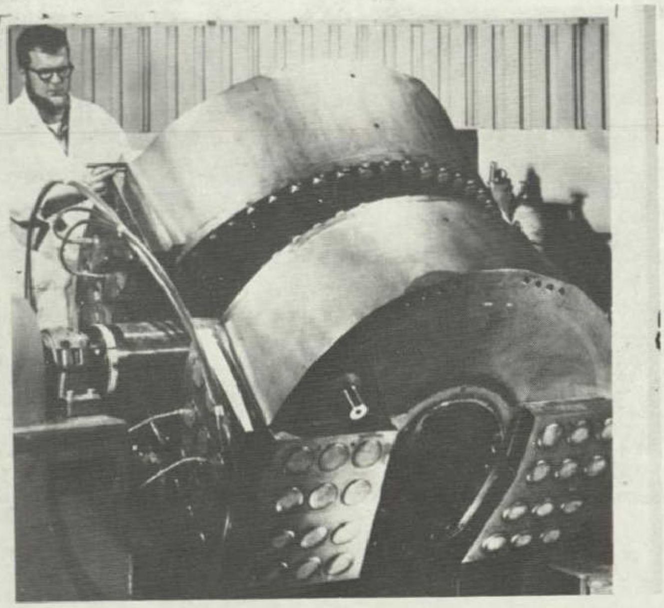


FIGURE 7

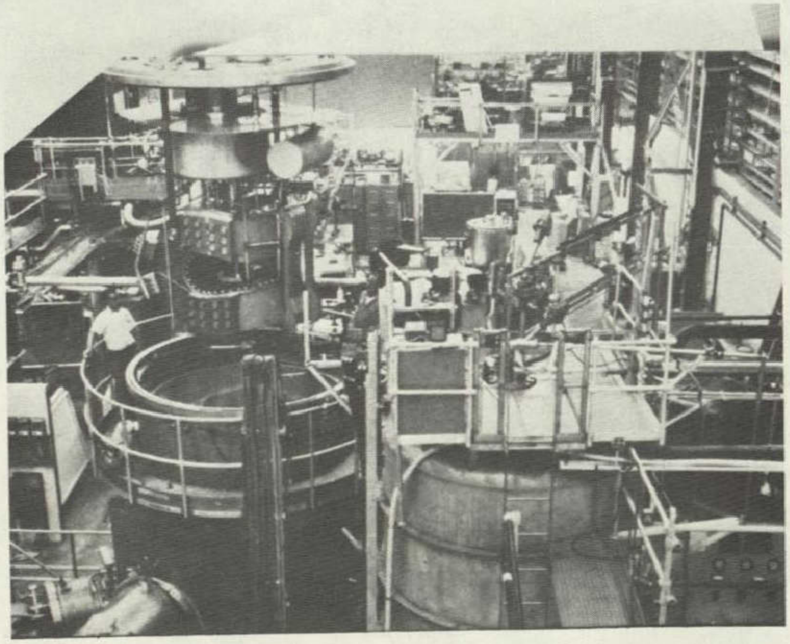


FIGURE 8

E-8772

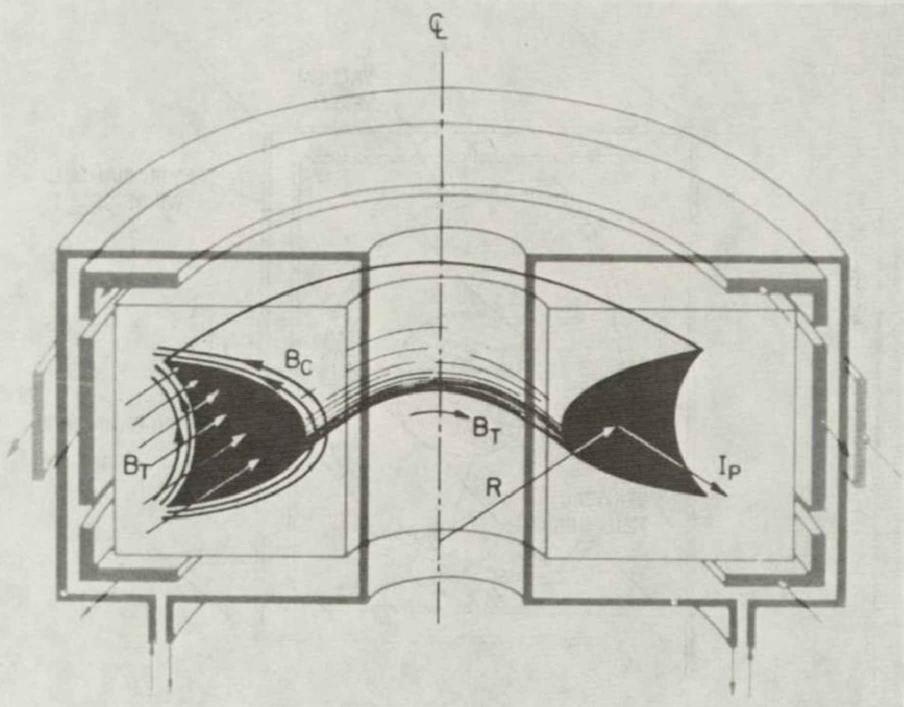


FIGURE 9

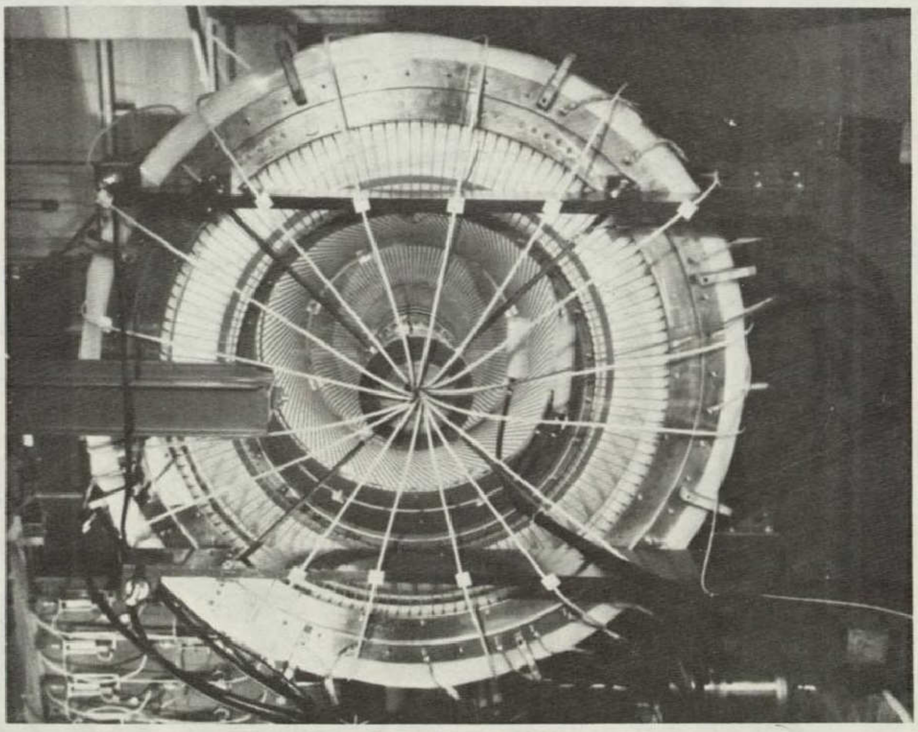


FIGURE 10

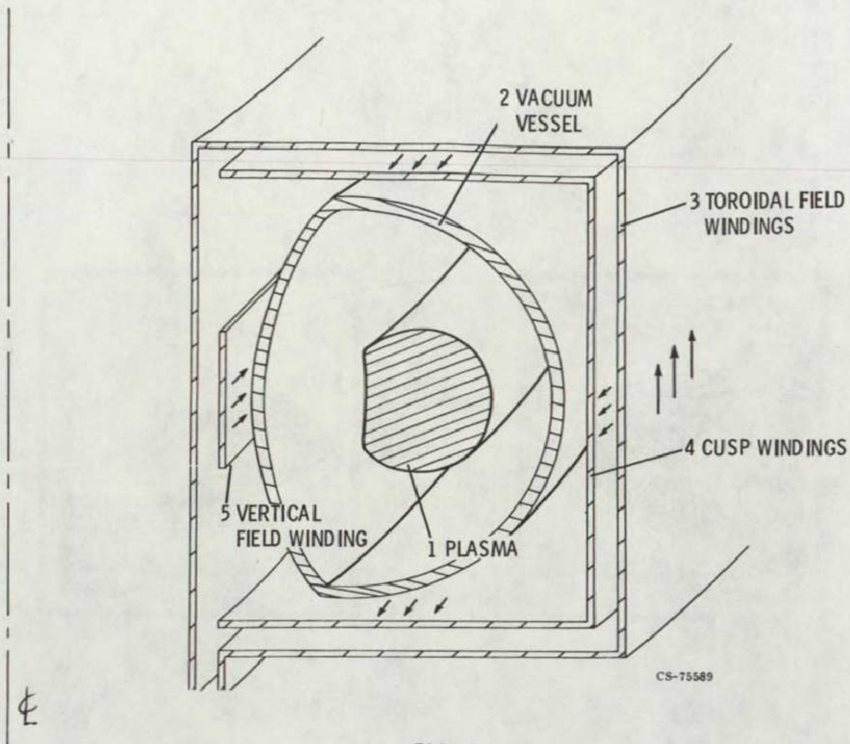


FIGURE 11

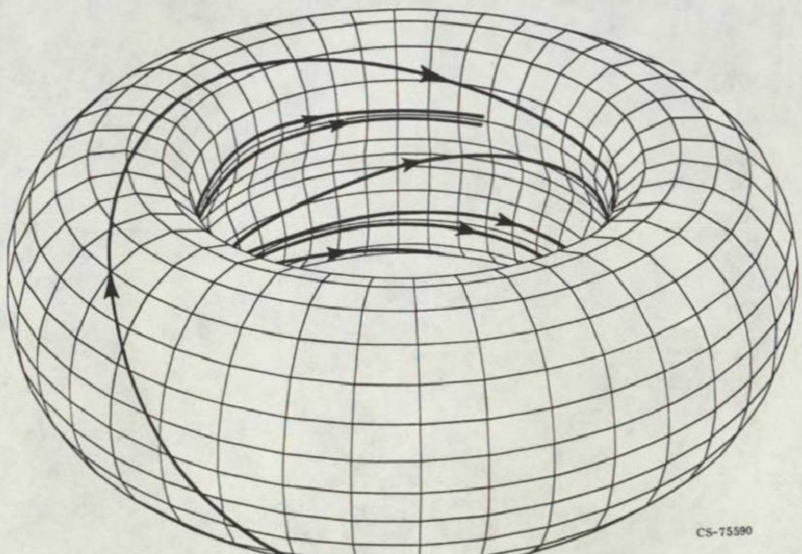


FIGURE 12

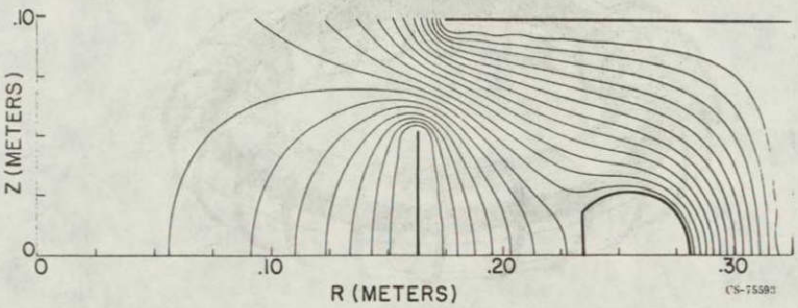


FIGURE 13

E-8772

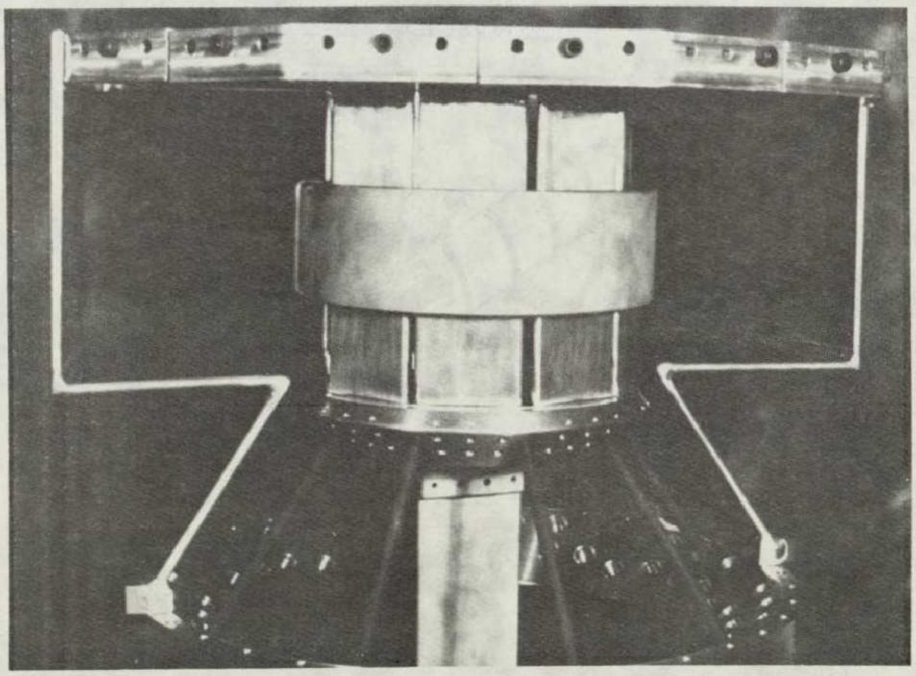


FIGURE 14

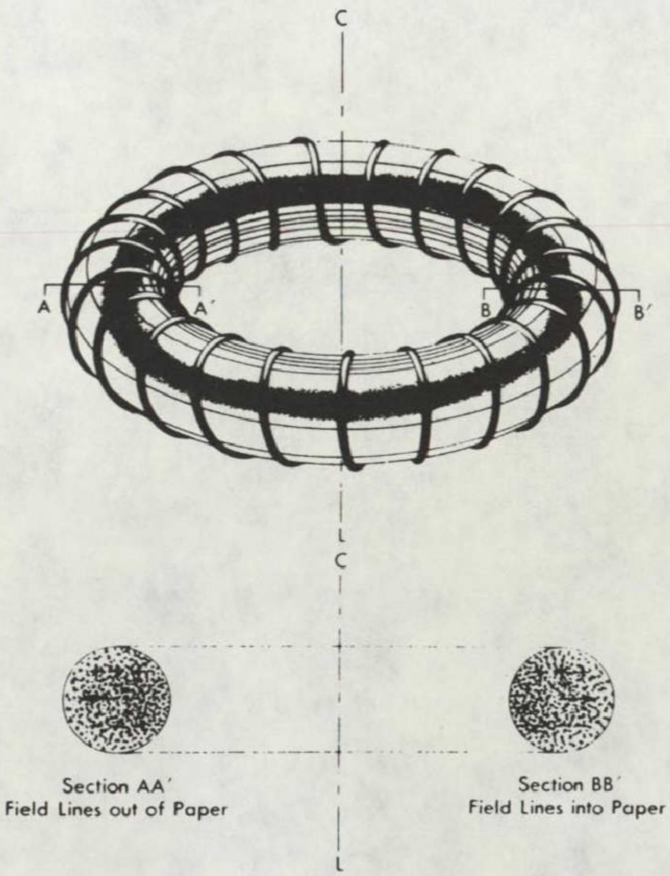


FIGURE 15

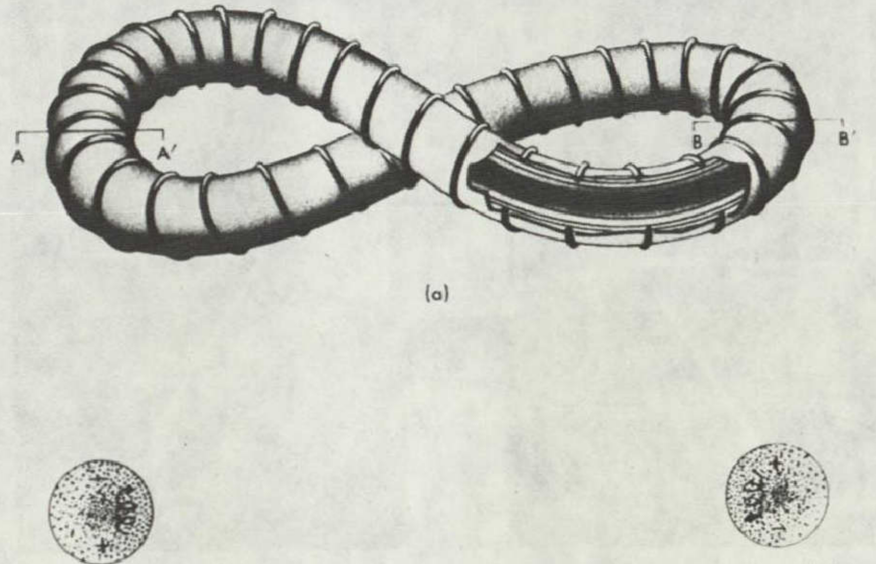


FIGURE 16

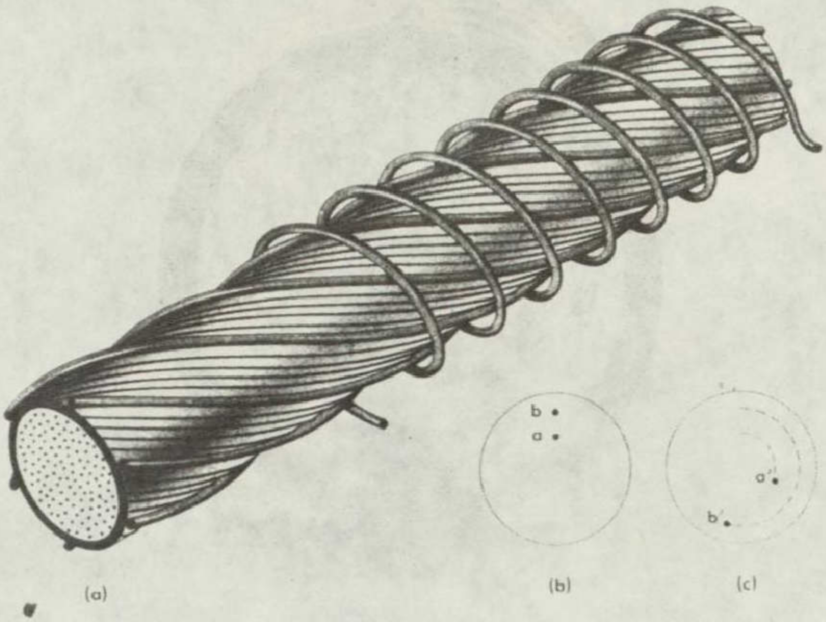


FIGURE 17

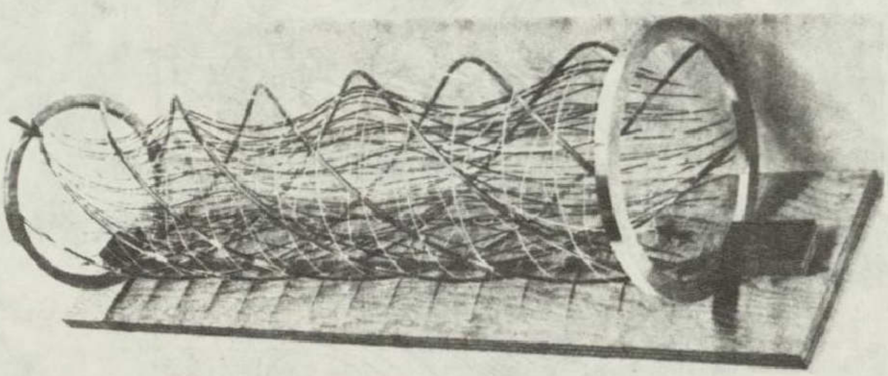


FIGURE 18

E-8772

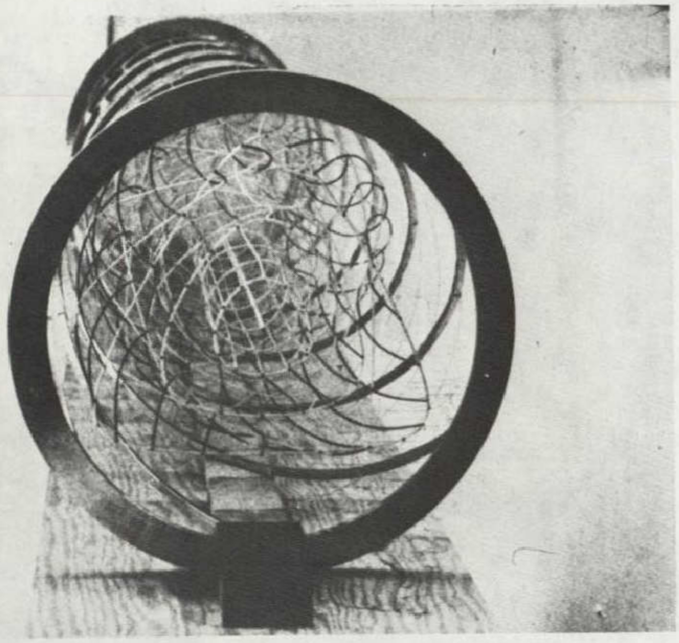
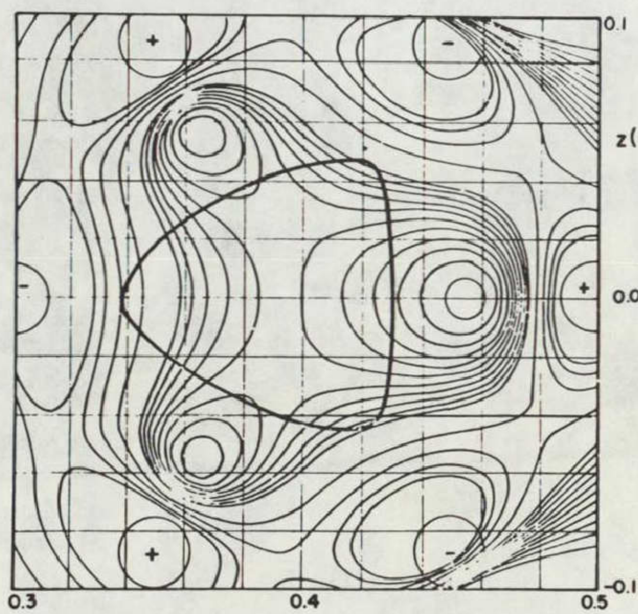


FIGURE 19



HIGH SHEAR |B| CONTOURS

FIGURE 20

E-8772

FIGURE 21

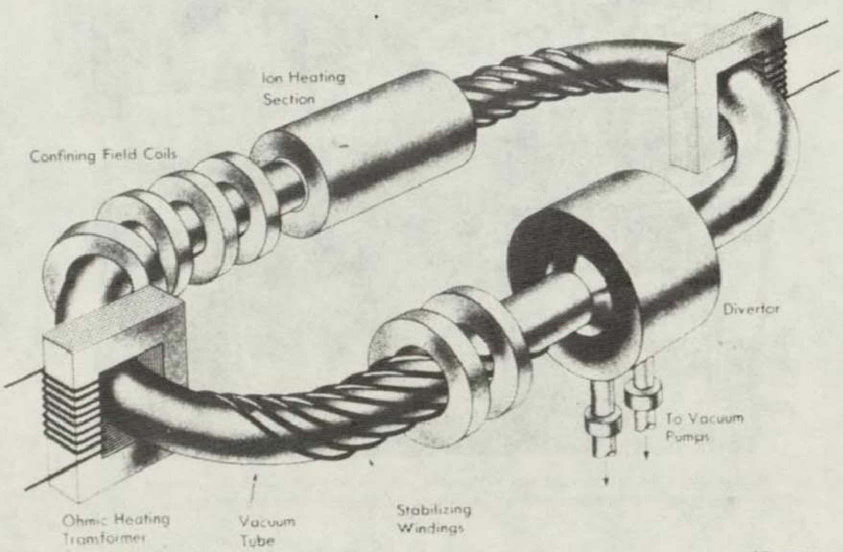


FIGURE 22

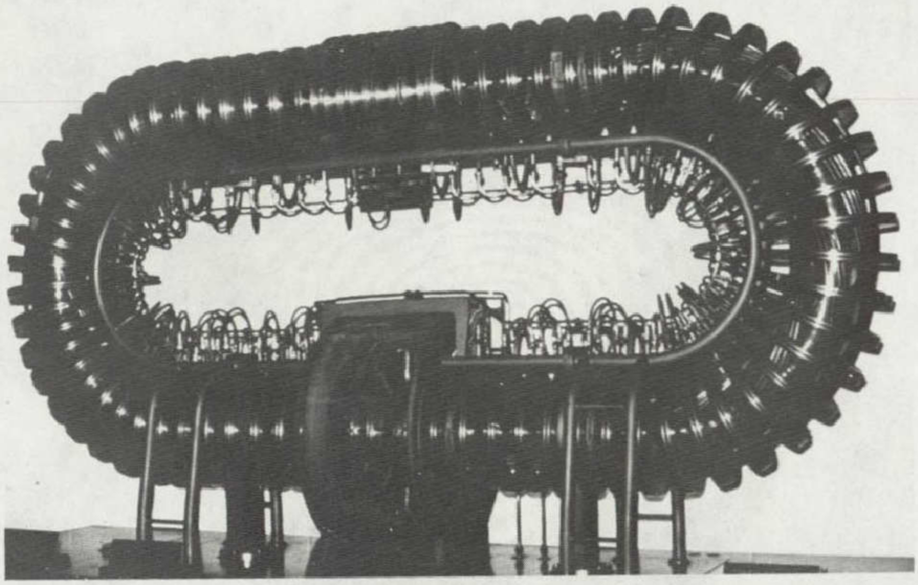
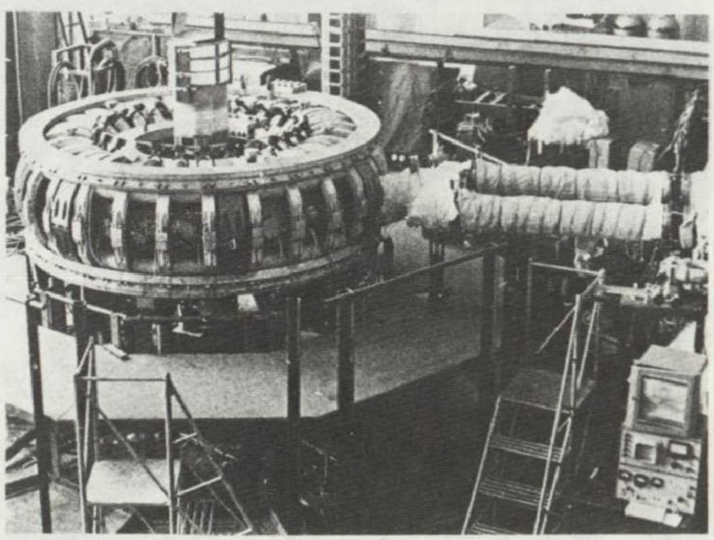


FIGURE 23



Stellarator L-2 at the Lebedev Institute in Moscow. In this machine, which has a major radius of 1 meter (similar to T-4), the plasma will be created by laser irradiation of solid pellets.

CS-75573

FIGURE 24

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

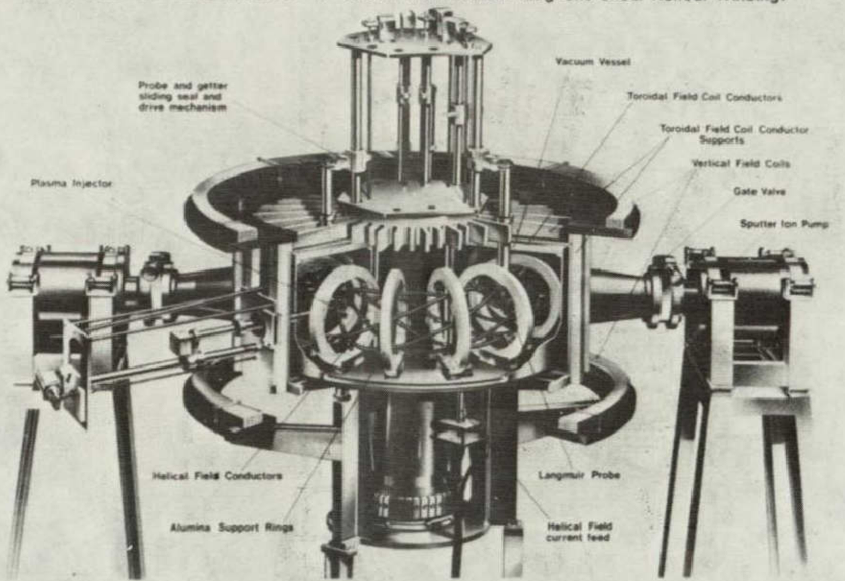


FIGURE 25

E-8772

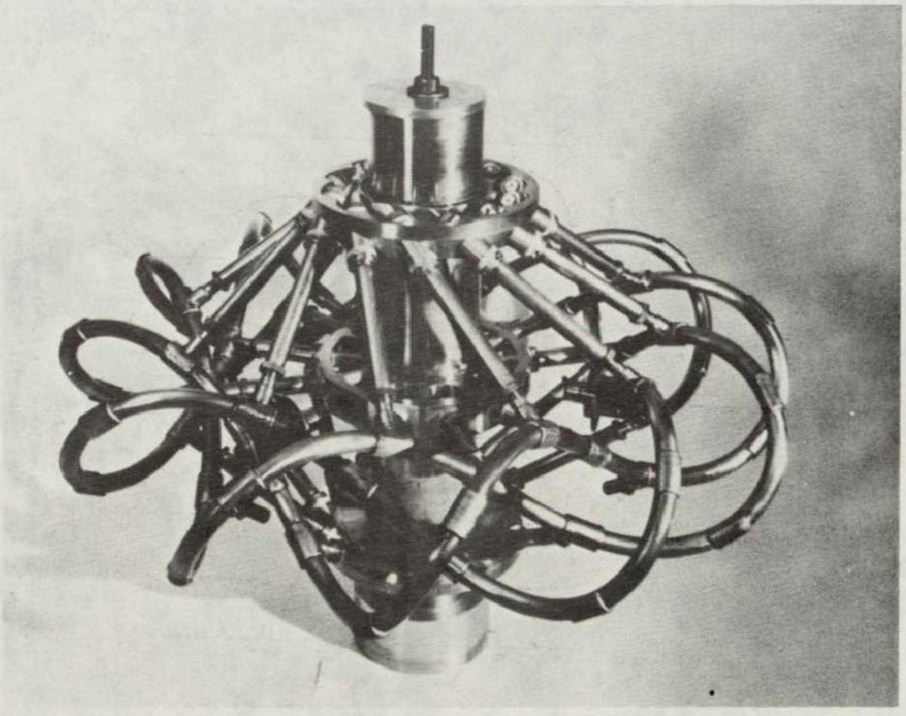


FIGURE 26

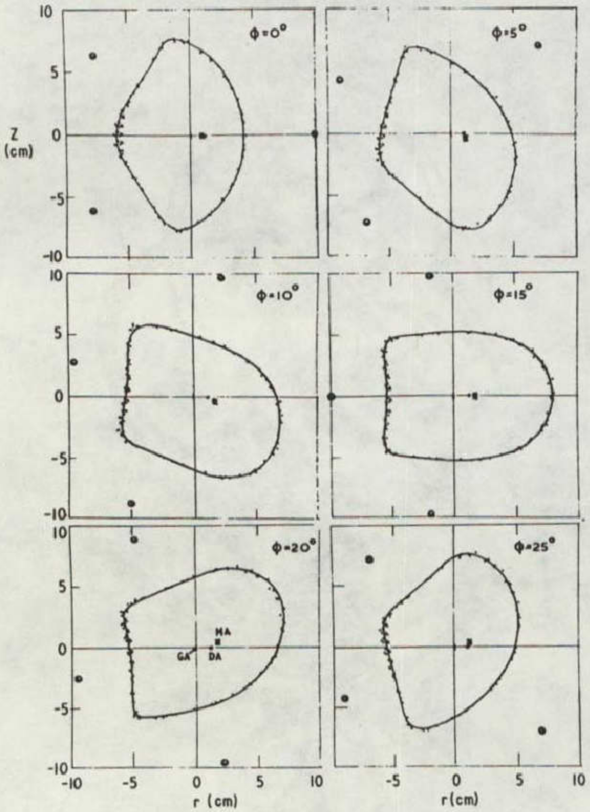
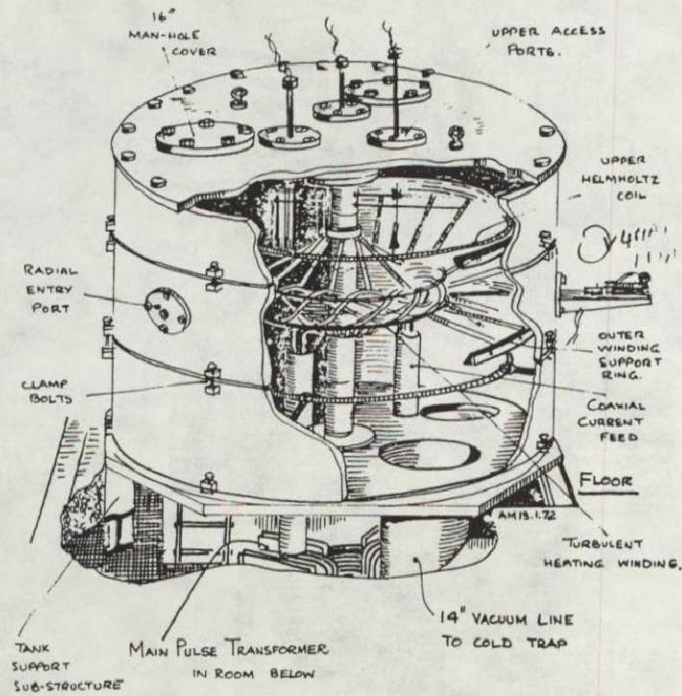


Fig. A2

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

FIGURE 27



AN IMPRESSION OF TORSO

FIGURE 28

E-3772

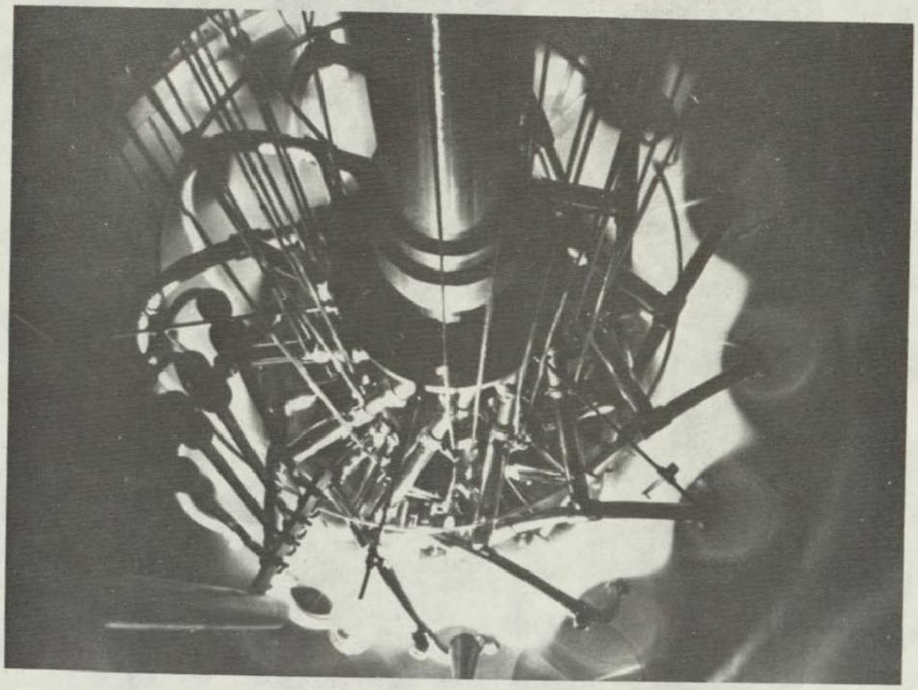


FIGURE 29

THE BUMPY TORUS CONCEPT

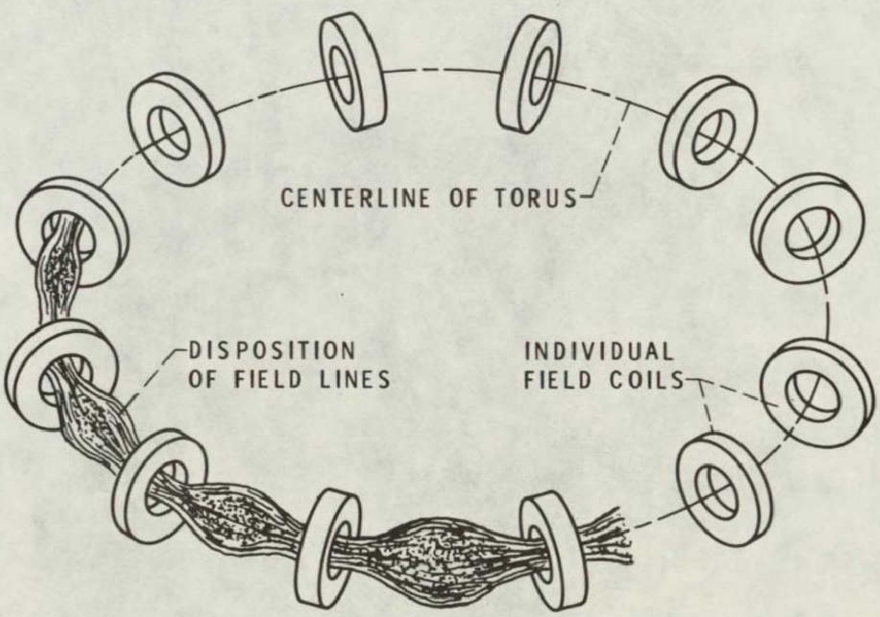


FIGURE 30

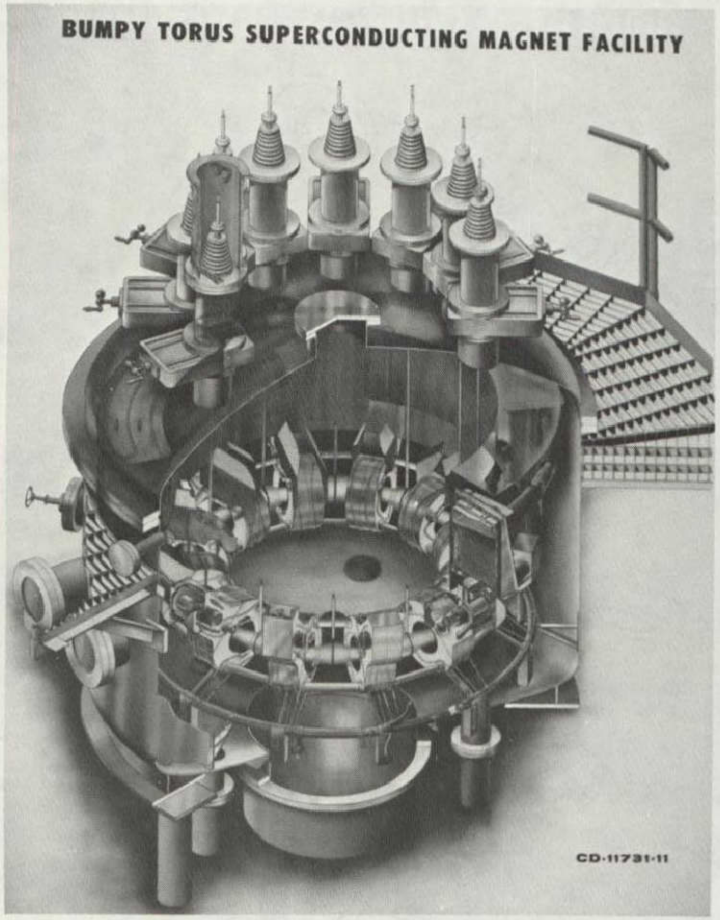


FIGURE 31

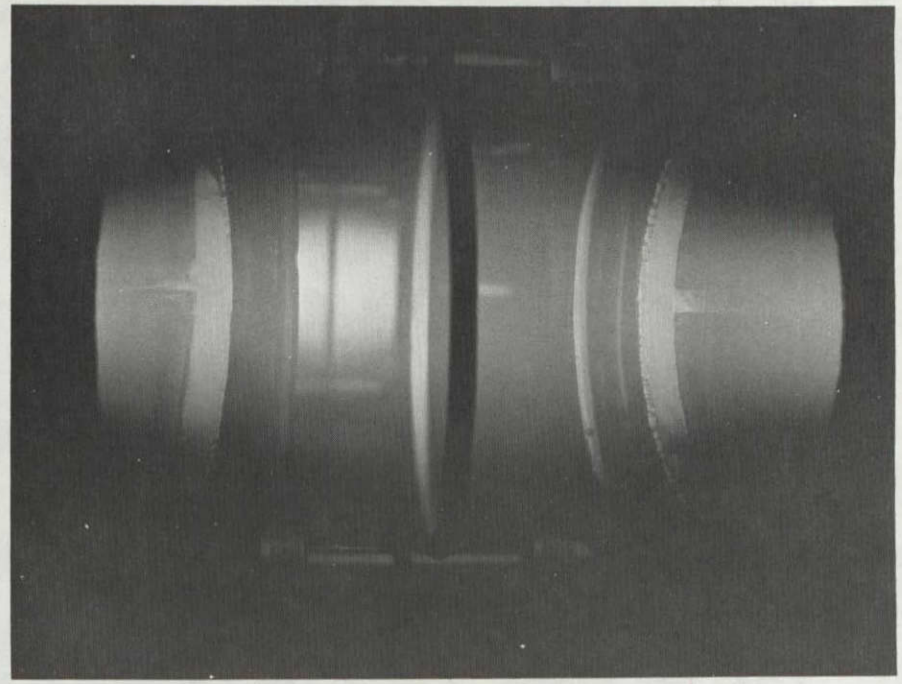
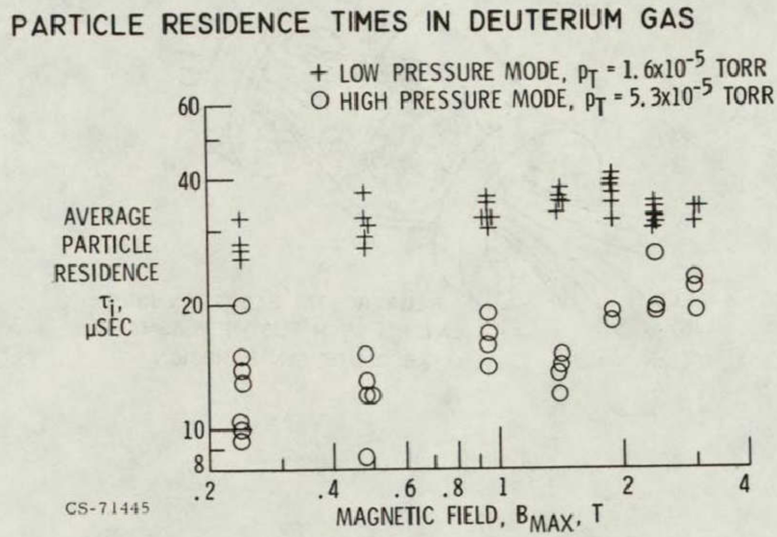


FIGURE 32



CS-71445

FIGURE 33

E-8772

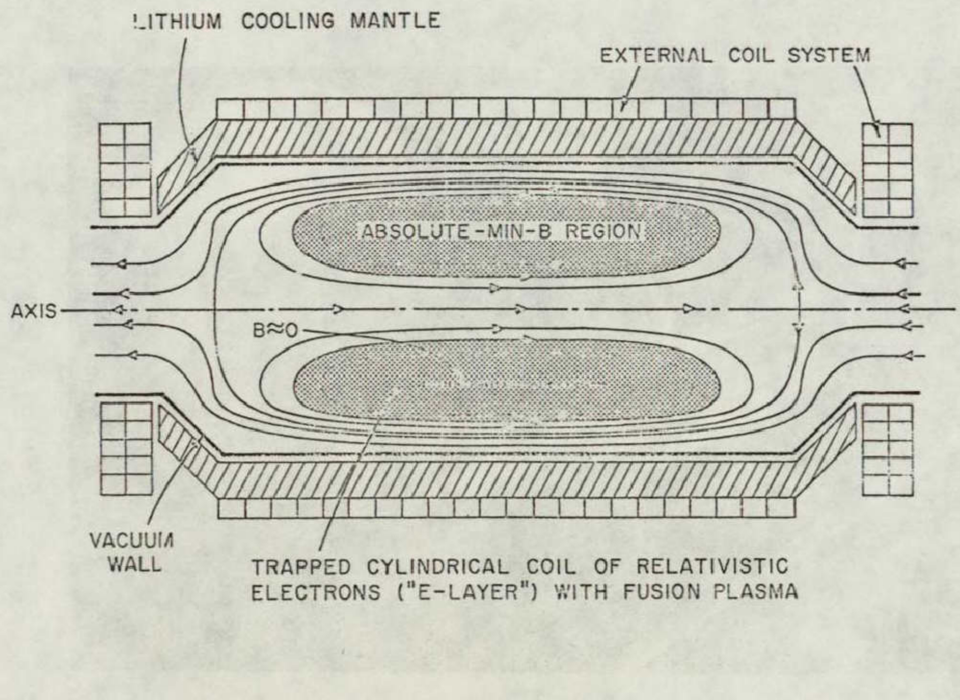


FIGURE 34

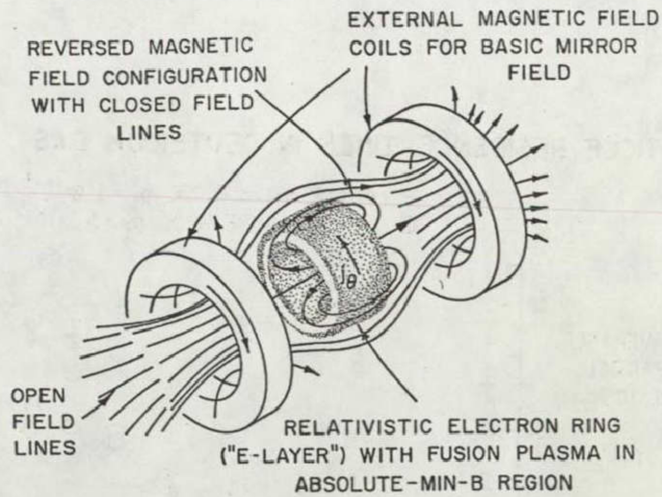


FIGURE 35

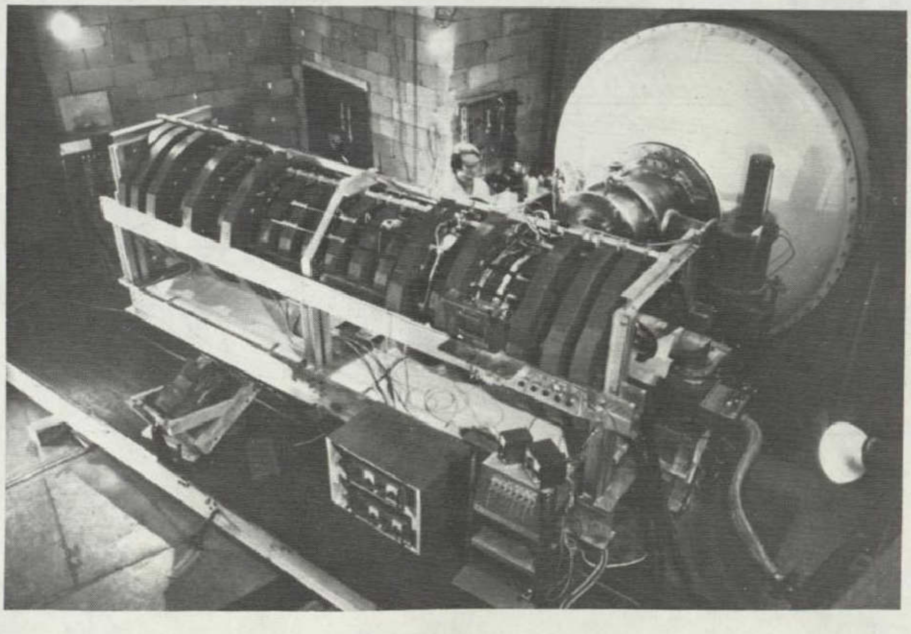


FIGURE 36

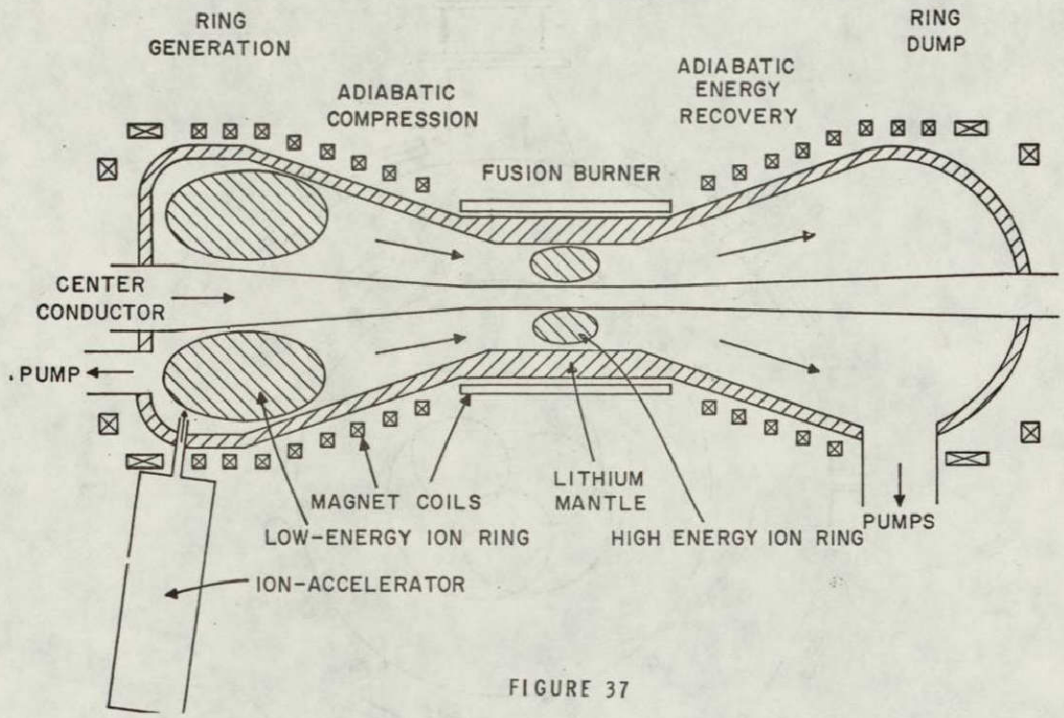


FIGURE 37

E-8772

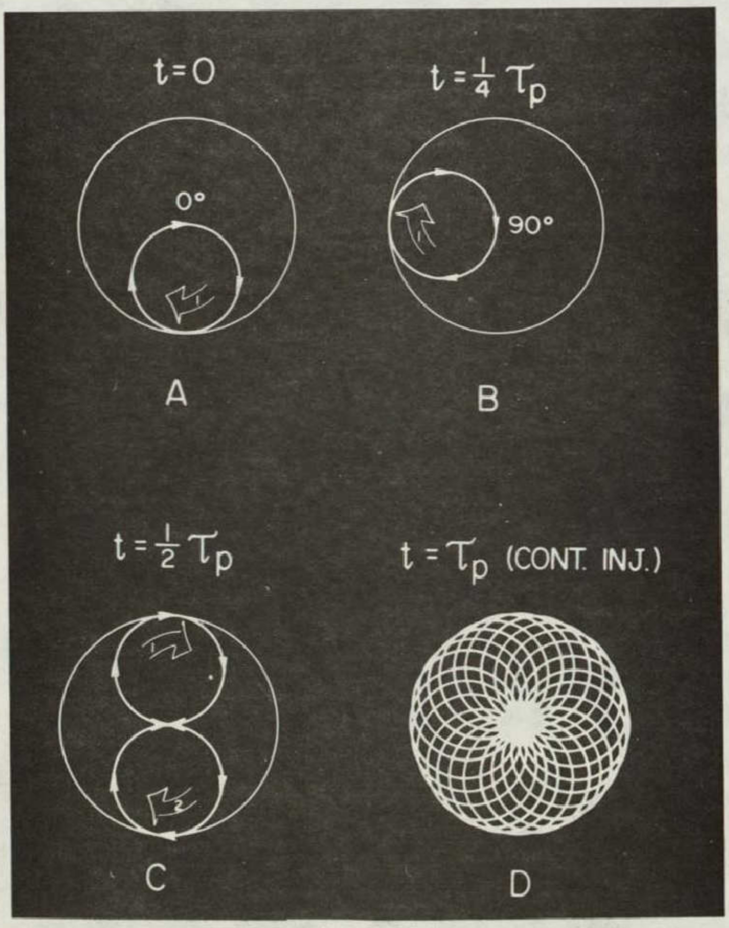


FIGURE 38

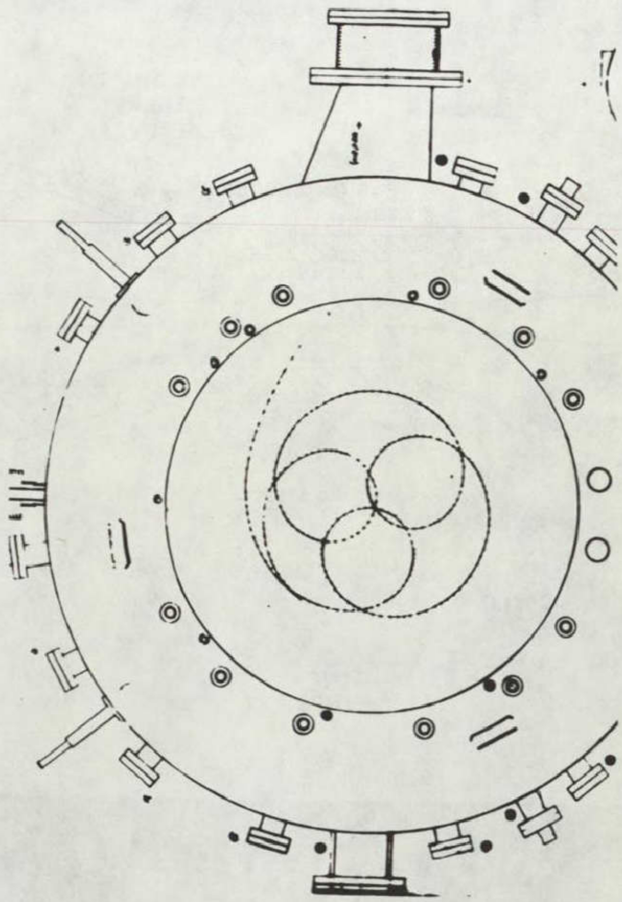


FIGURE 39

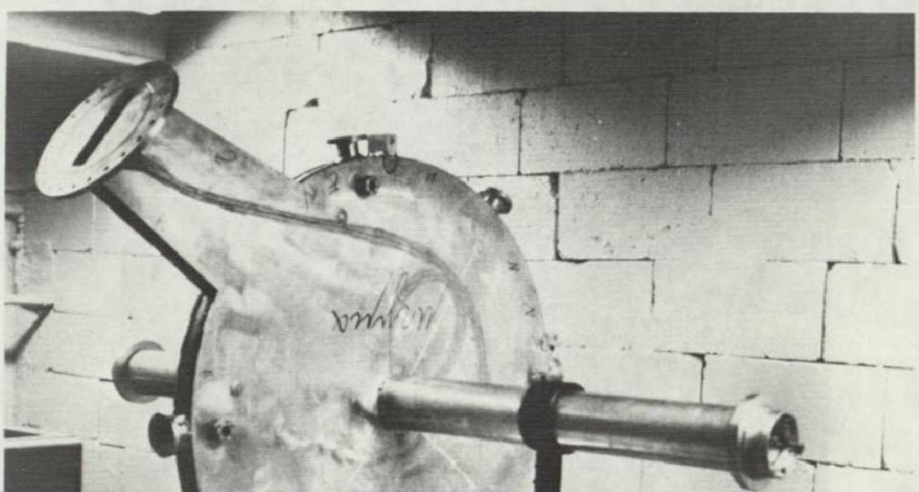


FIGURE 40

E-8772

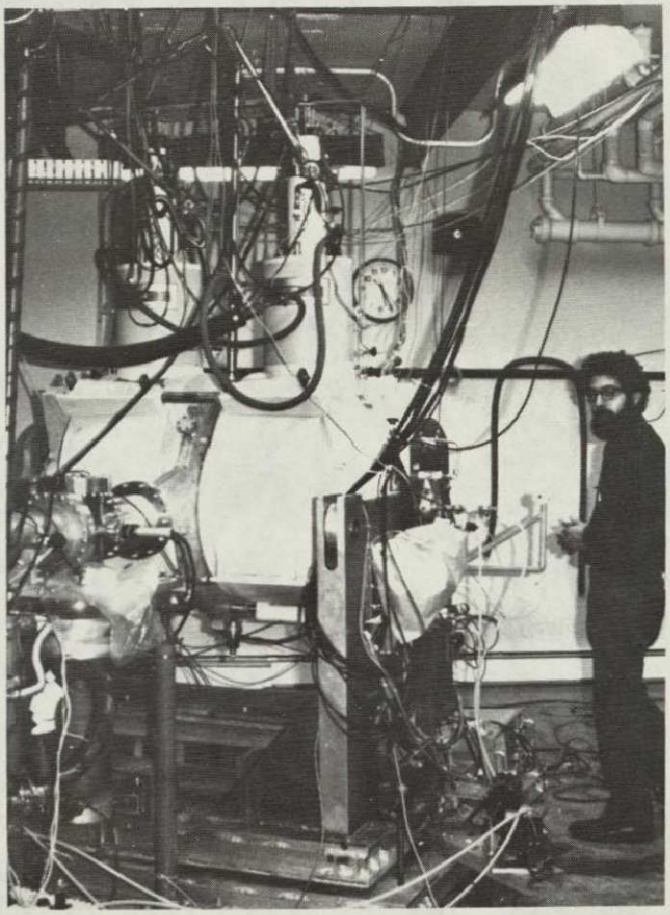


FIGURE 41