1 PPPL-1975

2 UC20-A,D

①

I-8102

PPPL-1975

Dr. 1214

CURRENT STATE OF MAGNETIC-FUSION ENERGY RESEARCH

By

J.L. Johnson and K.E. Weimer

FEBRUARY 1983

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

MASTER

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CO-3073.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PPPL--1975

DE03 007242

CURRENT STATE of MAGNETIC-FUSION ENERGY RESEARCH

J. L. Johnson* and K. E. Weimer

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey 08544, U.S.A.

ABSTRACT

With the improved understanding of plasma physics, progress is being made on several approaches to magnetic confinement for controlled thermonuclear fusion.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

*On loan from Westinghouse Research and Development Center, Pittsburgh, PA,

U.S.A.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

I. INTRODUCTION

It is well known that when two light nuclei fuse to form a heavier nucleus, the resultant material has less mass. The mass difference appears in the kinetic energy of the particles or in radiation. The most easily achievable nuclear reaction is between two hydrogen isotopes, where deuterium and tritium nuclei combine to form a helium ion and a neutron, releasing about 17.6 MeV of energy. The most promising way to realize this energy is to heat a plasma so that the thermal motion of the ions can overcome the Coulomb barrier (electrostatic forces). Calculations show that it is essential to hold a hot plasma, with a temperature of about 10 keV ($100,000,000^{\circ}\text{C}$), until the product of the density and the energy confinement time, $n\tau_E$, is greater than $10^{20} \text{ m}^{-3}\text{sec}$. The two major avenues to this goal are magnetic confinement, where the plasma density is about 10^{20} m^{-3} and the individual particles in the plasma remain well-confined for about a second before diffusing out into a collection chamber, and inertial confinement, where the density is about a thousand times that of a solid and the corresponding very brief confinement time is long enough that sufficient reactions can occur before the plasma blows itself apart.

The program on inertial-confinement fusion was initiated in the late 1960's when high-power lasers became available. They made it possible to concentrate a large amount of energy on a small target, heating it to the point where significant fusion could occur. This work, including the use of electron beams as well as of light and heavy ion beams as the energy source, is progressing. Much effort in this field relates to pellet design and is closely tied to weapons work. For this reason, parts of the program are classified, and it is difficult to assess its status. We therefore limit our discussion to work on magnetic confinement. The feasibility of inertial-

confinement fusion has been reviewed recently.^{1,2}

The first recognition that magnetic fields could be used for plasma confinement occurred in the late 1940's and early 1950's, with studies initiated in England, the United States, and the Soviet Union. This work was quickly classified because it was realized that success would provide a copious source of high-energy neutrons which could be used to generate fissionable material. At the First International Conference on the Peaceful Uses of Atomic Energy in 1955, the great Indian physicist, H.J. Bhabha, announced that these programs existed and encouraged international cooperation in this new research field. This led to the complete declassification of the program and to free exchange of information at the Second International Conference in Geneva in 1958. Since that time the program has been characterized by its openness and by a spirit of cooperation. The International Atomic Energy Agency, in Vienna, has organized nine International Conferences on Plasma Physics and Controlled Nuclear Fusion Research where papers on both magnetic and inertial confinement have been presented. Thirty-four nations were represented at the latest Conference held in Baltimore, Maryland, USA, September 1-8, 1982. Many cooperative agreements exist, and circulation of laboratory reports and exchanges of personnel, sometimes for extended periods of time, proceed on a continuing basis. Multinational involvement in designing, building, and operating experimental devices is an everyday occurrence.

Several approaches to magnetic confinement of a hot plasma were proposed in the 1950's³ and are still being actively pursued. The two basic ideas involved (1) closed systems where the magnetic field lines define surfaces of constant pressure in toroidal configurations and (2) open systems where constancy of the magnetic moment of the particles provides confinement.

Tokamaks, reversed-field pinches, and stellarators characterize the first type. Mirror machines and theta pinches typify the second. Although the Elmo Bumpy Torus device is toroidal, the concept evolved from the mirror approach. We will discuss each of these devices in the order judged most promising by the United States Department of Energy, Division of Magnetic Fusion Research.⁴

II. TOKAMAK

The tokamak approach is illustrated in Fig. 1. The main plasma confinement is provided by a toroidal field, with current in the plasma as well as some in axisymmetric external coils producing a poloidal field. This work evolved from studies of pinch discharges where the self-constriction of the toroidal plasma current creates a magnetic field that can confine a plasma. It was realized early in the program that a sufficiently large toroidal magnetic field must be provided so that the safety factor $q = aB_T / R B_P$ is greater than one, or else the system would be unstable to a large-scale Kruskal-Shafranov kink instability. Here R and a are the major and minor radii of the discharge, and B_P and B_T are the poloidal and toroidal components of the magnetic field. The first major breakthrough in the fusion program occurred in 1969 when it was shown that electron temperatures of 1 keV were attained in the T-3 tokamak at the Kurchatov Institute in Moscow. This led to the development of large tokamak programs in centers throughout the world.

As soon as the T-3 results were confirmed, the Model-C Stellarator at the Princeton Plasma Physics Laboratory was converted to the ST tokamak and all the Soviet results were verified. Many other devices have operated successfully and have provided a solid understanding of the properties of tokamaks. Machine parameters for many of these devices are given in Table 1

of Reference 5. The second major breakthrough in the program came in 1978 with the use of neutral injection to form well-diagnosed plasmas with $T_i \approx 7$ keV. Since that time the emphasis has shifted from one of demonstrating the feasibility of tokamak confinement to one of optimizing its favorable economic reactor characteristics.

Operation with nT_e approaching the necessary value for ignition has been successful in Alcator C. It has generally been observed that energy confinement is poorer than theoretically predicted. The energy transport associated with the ions behaves neoclassically; that is, their energy loss agrees with that calculated using classical theory but taking into account the enhanced loss associated with particles trapped between regions of higher magnetic fields along the magnetic field lines. On the other hand, the losses associated with electron transport are anomalously large. No good theoretical explanation has been obtained, but it is generally believed that the increased loss is due to microturbulence associated with localized instabilities driven by the toroidal currents. Nevertheless, the present measurements of plasma thermal conductivity in tokamaks, $\chi \sim 10^4 \text{ cm}^2\text{sec}^{-1}$, are in the range required for reactor operation. There is still some question as to how this scales to reactor parameters. In systems with little auxiliary heating beyond that associated with ohmic heating by the toroidal current, the confinement follows Alcator scaling, $\tau \propto na^2$. Recent studies with higher power input show a tendency for saturation below this prediction. One of the most significant results reported at the Baltimore meeting was that a regime in which this saturation does not occur has been investigated in ASDEX. It entered this optimized regime during operation with noncircular plasma cross sections with a divertor to ensure low-impurity operation. It was reported more recently that operation in this good-confinement regime has also been achieved in

Doublet-III using an elongated configuration. The improved operation with noncircular cross sections demonstrated in these experiments represents an important advance.

For a tokamak reactor to be viable economically, it is necessary that stable operation be achieved with $\langle \beta \rangle > 5\%$. Here $\beta \equiv 8\pi p/B^2$ measures the ratio of material pressure confined to that associated with the magnetic field, and the braces indicate an average over the plasma volume. Since the fusion power scales as $\beta^2 B^4$, even a small improvement in β can significantly increase performance. It is generally believed that β is limited mainly by magnetohydrodynamic instabilities, with stability criteria for large-azimuthal-number ideal ballooning modes providing the limit. Good agreement between experimental determination and theoretical predictions of the critical β have been obtained with the ISX device. The amount of auxiliary heating power generally available (typically less than 3MW of neutral beams) is too small to test the magnetohydrodynamic theory at appreciable values of β in the larger devices. These studies are therefore carried out with reduced values of the toroidal field B_T . It is, however, necessary to maintain the poloidal field strength B_p for good beam trapping and energy confinement. This requires operation with small values of the safety factor q , which in turn can lead to losses associated with kink and tearing modes. Under these conditions, stable operation with circular plasma cross sections has been achieved in ISX with $\langle \beta \rangle = 2.2\%$, in JFT-2 and T-11 with $\langle \beta \rangle = 2.8\%$, and in PLT with $\langle \beta \rangle = 3.0\%$. The best result was obtained in a noncircular plasma in Doublet-III where $\langle \beta \rangle = 4.6\%$.

Plasma heating in tokamak reactors is not considered to be a fundamental issue since the heating efficiency achieved in present neutral-beam experiments is adequate for reactor needs. As the size of the devices

increases, it will be necessary to work with higher energy beams. This has justified an effort to develop negative-ion beam sources. It would appear to be much more cost effective to replace the neutral injector with radio-frequency heating systems, and much effort is being expended in this direction. The most successful approach has made use of waves in the ion-cyclotron-frequency range. Increases of well over 1 keV in the ion temperature have been obtained on TFR using the ion-ion hybrid resonance and on PLT using minority heating with ^3He and ^1H as well as the second-harmonic resonance. In all of these cases, the heating efficiency was nearly adequate for reactor operation.

A more convenient approach from the point of view of microwave technology would be to work in the lower-hybrid-resonance frequency range so that a wave guide, rather than an antenna inside the device, could be used. Although the heating observed with this approach has not been as good as with ion-cyclotron heating, the results are encouraging. Some success has also been achieved with Alfvén-wave heating and with the use of electron-cyclotron resonance waves for direct heating and control of the electrons.

Reactor studies show that long-pulse or even steady-state tokamak operation would be very desirable, mainly because of thermal and mechanical fatigue considerations for the first wall. Development of techniques for noninductive current drive under reactor conditions is required. The use of lower-hybrid waves for current drive has proven to be quite successful. Currents of 420 kA and of 165 kA have been sustained for 0.3 sec and for 3.5 sec, respectively, in PLT. The best results have been achieved in low density plasmas, $n < 10^{19} \text{ m}^{-3}$, but reasonable currents have been obtained in Alcator-C with $n \sim 6 \times 10^{19} \text{ m}^{-3}$. Since it is believed that the momentum transfer is provided primarily because of a skewed electron distribution

function in velocity space, it is not yet clear that these encouraging current-drive results can be extrapolated to reactor conditions.

A second problem that must be solved for long-pulse operation concerns control and removal of the diffusing plasma and impurities. Present-day experiments are encouraging in that they show no impurity accumulation. It appears that a pumped limiter will suffice for removal of the escaping plasma and impurities from the reaction chamber. Some experience has been obtained with systems where a magnetic divertor separates the plasma from the vessel wall. Experiments on PLT, Doublet-III, ASDEX, DITE, and TO-2 have all demonstrated effective channeling of both particle and heat outflow into the divertor chamber. Particularly encouraging results have been obtained in regimes where the plasma density is high and its temperature is low in the scrape-off layer, eliminating sputtering. The improvement in confinement of a diverted plasma that was observed in ASDEX is particularly exciting.

One problem that concerns tokamak designers is the occasional occurrence of disruptions where confinement is rapidly destroyed and the energy is dumped on the wall of the system. This behavior is generally believed to be associated with magnetohydrodynamic kink modes with azimuthal mode number $m = 2$. If the safety factor q is two on some magnetic surface inside the plasma, the instability will grow, and magnetic islands will develop. Disruptions usually occur if these islands overlap analogous ones on surfaces with $m=1$ or $m=3$, or reach the limiters. Control of the safety-factor profile may be sufficient to avoid these problems.

With the improved understanding of tokamak behavior, it is time for a new generation of larger devices to come on-line. This is happening. The Tokamak Fusion Test Reactor, TFTR, at Princeton (Fig. 2) is now beginning full-scale operation. It should operate at breakeven in 1986. This experiment has been

defined as the demonstration of scientific feasibility. In addition to this important demonstration, this device should provide the scaling relations which will be needed to proceed to reactor conditions. The Joint European Tokamak (JET) at Culham, England, will become operational a few months after TFTR. It too should improve our understanding of plasma behavior. It is expected that it will demonstrate breakeven operation with a D-T plasma mixture, probably in 1988. Two other large tokamaks, JT-60 at the Japanese Atomic Energy Research Institute, and T-15 at the Kurchatov Institute in Moscow, are being constructed.

A large international effort, with representatives from Euratom, Japan, the United States, and the Soviet Union, has been mounted to design the device that should follow this group of machines. This has culminated in the International Tokamak Reactor (INTOR) design study. Each of the groups involved in this effort has its own intensive design studies. Several good review articles on tokamaks are available.⁵⁻⁹

To summarize, there has been sufficient progress in tokamak research that the focus has changed from one of scientific feasibility to one of engineering and economic optimization.

III. MIRROR

The use of mirror fields for magnetic confinement was one of the first approaches to fusion. It is based on the concept that the magnetic moment $\mu = mv_{\perp}^2 / 2B$ of a particle is an adiabatic invariant that must be conserved. Thus, if the magnetic field increases as one goes out along the field line, as in Fig. 3, the perpendicular velocity must increase. Since the energy of the particle must also be conserved, this means that the parallel component of the velocity must decrease. At some distance, the field magnitude may be

sufficiently large that the particle will be stopped and reflected back. The simplicity of the approach, together with the possibility for steady-state operation, makes it particularly attractive.

The major limitation is that there is a large class of particles which is not confined. If the pitch angle ($\theta \equiv \cot^{-1} v_{\parallel}/v_{\perp}$ of the particle at the center of the device) is too small, the particle will continue through the mirror and be lost. Thus, there exists a loss cone in velocity space which is inversely proportional to the mirror ratio, $B_{\max}/B_{\min}$. The big problem is that scattering in velocity space by collisions moves particles into this loss cone much more rapidly than it transports them across the magnetic field lines so that end loss is large. However, since most of the particle and energy loss in mirrors is associated with a flux of charged particles through the mirror throats, it is possible to recycle much of the energy directly. Then thermal conductivity across the magnetic field lines, $\chi \sim 10^{-1} \text{ m}^2\text{sec}^{-1}$, would provide adequate confinement.

Simple mirrors have unfavorable field line curvature. If an interchange of magnetic field lines containing the same amount of magnetic flux were made, more material would be moved outwards than would be brought in, and the plasma could expand without changing the magnetic energy. Since the associated decrease in potential energy would be converted to kinetic energy, the system is unstable with respect to interchange or flute instabilities. The first major breakthrough in the mirror program came in 1961 when M. S. Ioffe, at the Kurchatov Institute in Moscow, added currents in straight external coils parallel to the magnetic axis to twist the magnetic field lines and provide a minimum-B field, with the field line curvature pointing outward everywhere. This eliminated the magnetohydrodynamic instabilities and provided a significant increase in confinement. The configurations needed to obtain

these favorable systems have evolved, with the magnetic fields now produced by yin-yang or baseball coils.

It was soon recognized that loss-cone instabilities enhance the rate at which particles are scattered in velocity space and acquire too much parallel velocity to be confined. The second mirror breakthrough came when it was found that these modes could be stabilized by having a warm plasma stream through the ends of the mirror. This is presently being accomplished with gas puffing, but, in the thermonuclear regime, the plasma outflow would perform this function.

Because of the large inherent end loss, the concept has had a poor economic prognosis. The third mirror breakthrough came relatively recently when the tandem mirror concept was proposed. With the advent of high-power neutral beams, it has become possible to trap hot-ion plasmas in the two end-plug regions. These create electrostatic fields which, in turn, hold the plasma in an inner central reacting cell. In this system, there is a region of unfavorable curvature between the central cell and the outer stabilizing yin-yang anchors. Thus, the plasma β is limited by ballooning modes. Even so, present experiments indicate that β -values of 30% can be sustained. The most recent development in the mirror concept was the recognition that a satisfactory electrostatic potential could be generated if the ions in the plug regions were much hotter than the electrons so that the electrons could be thermally isolated from the hotter ones in the central region. This can be accomplished by using electron-cyclotron-resonance heating to introduce a local, energetic-electron plug. Several devices to investigate these concepts are currently being operated or under construction. Parameters for some of the devices are given in Table II of Reference 10. Microinstabilities are being reduced in TMX-U and GAMMA 6 by injecting the neutral beams at an angle so

that the energetic ions slosh between the two mirrors.

Although the mirror approach has lost its simplicity, it is still a viable candidate for a fusion reactor. Steady-state, high- β operation is possible. Although the confinement that has been achieved is quite low, $n\tau_E$ is less than $10^{17} \text{ m}^{-3}\text{sec}$, scaling considerations indicate that it should have satisfactory reactor performance. GAMMA 10, completed in March, 1982 at Tsukuba University in Japan, is expected to be in full operation in the spring of 1983 and the Mirror Fusion Test Reactor, MFTF-B, should become operational in Livermore, California, in 1986. Some useful review papers on the mirror program have appeared.¹⁰⁻¹⁴

IV. ELMO BUMPY TORUS

The leading alternate concept in the United States fusion program is the Elmo Bumpy Torus (EBT)¹⁵ (Fig. 4), in which the mirror end loss is eliminated by mounting a string of mirrors around a torus so that each magnetic field line is closed. The plasma forms surfaces of constant pressure with $p = p(\oint dl/B)$. Electron-cyclotron-resonance heating is used to create high-temperature electron annuli in each mirror cell. Since these rings are rigid, they can stabilize the interchange instabilities if the pressure gradients are confined to the annular region. Successful operation has been obtained in EBT-S at Oak Ridge with densities of $2 \times 10^{18} \text{ m}^{-3}$ and $n\tau \sim 10^{16} \text{ m}^{-3}\text{sec}$. Similar experimental results have been obtained on the Nagoya Bumpy Torus (NBT). The attractive reactor features of construction with small modular components and of steady-state operation will be attained if the assumed scaling of the physics is found to occur.

V. REVERSED-FIELD PINCH

The reversed-field pinch (RFP) program evolved from the early Z-pinch studies¹⁶ in which the self-constriction of an azimuthal current provides the poloidal confining field and a toroidal field is applied for stabilization (Fig. 5). The basic idea is similar to that of the tokamak; the major difference is that containment is achieved with the safety factor q less than one. The ideal magnetosonic modes are stabilized by having a conducting wall near the plasma and reversing the sign of the toroidal field to obtain a large shear in the magnetic field lines. If this works, the RFP would make a simpler, more attractive reactor configuration than the tokamak for several reasons. It could operate at high β , and the field inside the plasma would be larger than that at the coils, eliminating the need for superconducting magnets. Also, auxiliary heating would not be needed since the ohmic heating current should be sufficient.

The first large fusion device to be studied was the ZETA at Harwell, England. It was found that, after an initial period of turbulent activity, the plasma column settled into a force-free quiescent regime. Verification that the plasma can adjust itself into a stable configuration has also been obtained on the HBTX experiment at Culham, Eta-Beta II at Padua, Italy, and ZT-40 at Los Alamos. For some time, the behavior was limited significantly by energy losses associated with impurity radiation. These kept the temperature so low that classical diffusion destroyed the field reversal and allowed the plasma to become unstable in a short time. Recently it has been possible to heat the plasma to about 150 eV and extend the discharge duration to 20 msec with energy containment times of a few hundred microseconds. Parameters for some of the more significant devices are given in Reference 17. Although this approach has a long way to go, these recent experimental trends are

encouraging.

VI. COMPACT TORUS

If the RFP approach were successful, it would be nice to eliminate completely the toroidal field outside the discharge so that a coil structure encircling the plasma ring would be unnecessary. A sequence of compact plasma tori moving through a reaction chamber with separate formation, reaction, and disassembly regions could then be formed. Reactor design would thus be simple. The outlook for this program is analogous to that of a gambler betting on a number at a casino; the chance of winning is not large, but the cost of a chip is small.

Work has progressed on both the reversed-field theta pinch (with no toroidal field) and the spheromak (where both the toroidal and poloidal fields are induced in the plasma). The theoretically predicted instabilities, rotational modes in reversed-field theta pinches and tilting modes in spheromaks, have been observed, and some ideas for their stabilization are being implemented. Much remains to be done, but the approach looks promising.¹⁸

VII. STELLARATOR

If the tokamak approach experiences difficulties in becoming economically viable, it will be due to problems associated with the toroidal current that must be sustained to provide a rotational transform and thus twist the field lines to form magnetic surfaces for plasma containment. It has not yet been demonstrated that current drive will work at the densities needed for reactor operation. Thus it is quite possible that pulsed operation, with its concomitant need for energy switching and storage as well as for more frequent

materials replacements, will be required. We must still develop adequate control of and protection against the disruptions associated with current-driven tearing modes. Also, there is good reason to believe that the poor electron thermal conductivity observed in tokamaks is associated with this current. It is therefore comforting to know that the stellarator approach, in which the rotational transform is imposed from the outside without requiring a net toroidal current, is available as a possible direction for tokamak evolution.

The stellarator was one of the earliest approaches. It is the only concept that offers the possibility of steady-state operation with no external energy input to the plasma once thermonuclear conditions have been reached. The early devices had complicated and poorly controlled magnetic fields, and it is now generally believed that the observed poor confinement resulted from ergodicity of the magnetic surfaces.

In the last few years there has been significant progress. It has been well verified that confinement improves as the ohmic-heating current is decreased when an external transform is applied. Net-current-free operation in Wendelstein VII-A at Garching, FRG, and in Heliotron E at Kyoto, Japan, has demonstrated energy confinement that compares favorably with that in analogously sized tokamaks. A renewed interest in stellarators has led to significant advances in theoretical studies, especially in terms of beta limits and transport properties. The flexibility in magnetic surface shaping due to relaxing symmetry constraints at the magnetic axis and the lack of a net toroidal current provide a possibility for operation at higher β . More refined transport models indicate that adequate containment can be achieved. Similarly, adoption of the torsatron approach, where the forces on the coils are easily managed, or of modular coils may provide answers to the engineering

difficulties.

The stellarator concept has matured, with established programs existing at Garching, Kyoto, Kharkov, and Lebedev. A typical configuration is shown in Fig. 6, and parameters for some devices are given in Table I of Reference 19. Additional large experiments to investigate confinement of hot collisionless plasmas in three-dimensional configurations are needed. The results will be relevant not only to the stellarator as the alternate concept it is considered to be in the United States program, but as the natural extension of the tokamak path to toroidal confinement. Several review papers have been written in this area.¹⁹⁻²²

VIII. CONCLUSION

Progress towards controlled thermonuclear fusion is occurring on several devices. The focus is rapidly shifting from one of demonstrating physical feasibility to one of determining engineering and economic viability. It can be expected that scientific breakeven will be demonstrated in both tokamaks and mirrors in the next few years. Evolutionary concepts should be sufficiently well-investigated that, by then, the program can be advanced along its optimum path.

The success of the program is vitally important but will require a long, sustained, cooperative effort. By the time thermonuclear fusion power is commercially available, near the middle of the twenty-first century, the need for it will be urgent. Our oil and coal resources, if not nearly exhausted, may not be practical because of the possible, deleterious greenhouse effect associated with an increase in the CO_2 concentration in the atmosphere through the burning of these fossil fuels. Political as well as technical problems

with fission power and waste disposal may prevent fission from fulfilling the energy needs. Solar energy is so diffuse that it is difficult to see how it could make a large contribution without a significant increase in energy costs. The fusion program is our major hope for increasing the standard of living throughout the world as well as for reducing the friction between nations which is associated with the uneven distribution of our known energy resources.

ACKNOWLEDGMENT

This work was supported by the U.S. Dept. of Energy Contract No. DE-AC02-76-CHO-3073 with Princeton University. We thank H.P. Furth for letting us see and use his summary report on experimental papers at the Baltimore IAEA conference before its publication.

REFERENCES

- ¹N.G. Koval'skii, "Laser Thermonuclear Fusion" (in Russian), in Reviews of Science and Technology (Itogi Nauki i Tekhniki); Series, Plasma Physics (Seriya Fizika Plazmy), B.B. Kadomtsev, editor-in-chief, V.D. Shafranov, editor, VINITI (All-Union Institute of Scientific and Technical Information, Moscow, 1980), Vol. 1, Part 1, pp. 166-231.
- ²J.H. Nickolls, "The Feasibility of Inertial-Confinement Fusion," Phys. Today 35, 25-31 (1982).
- ³A.S. Bishop, Project Sherwood: The U.S. Program in Controlled Fusion, (Addison-Wesley Publishing Co., Reading, Massachusetts, 1958).
- ⁴J.F. Clarke, "An Interpretive Overview of the United States Magnetic Fusion Program," Proc. IEEE 69, 869-884 (1981).
- ⁵J. Sheffield, "Status of the Tokamak Program," Proc. IEEE 69, 885-917 (1981).
- ⁶P.H. Rutherford, "The Tokamak: 1955-80," Nucl. Fusion 20, 1086-1092 (1980).
- ⁷V.S. Mukhovatov, "Tokamaks" (in Russian), in Reviews of Science and Technology (Itogi Nauki i Tekhniki); Series, Plasma Physics (Seriya Fizika Plazmy), B.B. Kadomtsev, editor-in-chief, V.D. Shafranov, editor, VINITI (All-Union Institute of Scientific and Technical Information Moscow, 1980), Vol. 1, Part 1, pp. 6-118.
- ⁸M. N. Rosenbluth and P.H. Rutherford, "Tokamak Plasma Stability," in Fusion, edited by Edward Teller (Academic Press, New York, 1981), Vol. 1, Part A, pp. 31-121.
- ⁹H.P. Furth, "The Tokamak," in Fusion, edited by Edward Teller (Academic Press, New York, 1981), Vol. 1, Part A, pp. 123-242.
- ¹⁰T.C. Simonen, "Experimental Progress in Magnetic-Mirror Fusion Research", Proc. IEEE, 69, 935-957 (1981).
- ¹¹D.D. Ryutov, "Open Traps," Nucl. Fusion 20, 1068-1072 (1980).

- ¹²V.A. Chuyanov, "Adiabatic Magnetic Traps" (in Russian), in Reviews of Science and Technology (Itogi Nauki i Tekhniki); Series, Plasma Physics (Seriya Fizika Plazmy), B.B. Kadomtsev, editor-in-chief, V.D. Shafranov, editor, VINITI (All-Union Institute of Scientific and Technical Information Moscow, 1980), Vol. 1, Part 1, pp. 119-165.
- ¹³T.K. Fowler, "Mirror Theory," in Fusion, edited by Edward Teller (Academic Press, New York, 1981), Vol. 1, Part A, pp. 291-355.
- ¹⁴R.F. Post, "Experimental Base of Mirror-Confinement Physics," in Fusion, edited by Edward Teller (Academic Press, New York, 1981), Vol. 1, Part A, pp. 357-435.
- ¹⁵R.A. Dandl and G.E. Guest, "The Elmo Bumpy Torus," in Fusion, edited by Edward Teller (Academic Press, New York, 1981), Vol. 1, Part B, pp. 79-101.
- ¹⁶R.J. Bickerton, "Pinch Research," Nucl. Fusion 20, 1072-1075 (1980).
- ¹⁷D.A. Baker and W.E. Quinn, "The Reversed-Field Pinch," in Fusion, edited by Edward Teller (Academic Press, New York, 1981) Vol. 1, Part A, pp. 437-475.
- ¹⁸H.P. Furth, "The Compact Torus," J. Vac. Sci. Technol. 18, 1073-1080 (1981).
- ¹⁹J.L. Johnson, "The Stellarator Approach to Toroidal Plasma Confinement," Nucl. Technol./Fusion 2, 340-361 (1982).
- ²⁰K. Miyamoto, "Recent Stellarator Research," Nucl. Fusion 18, 243-284 (1978).
- ²¹V.D. Shafranov, "Stellarators," Nucl. Fusion 20, 1075-1083 (1980).
- ²²J.L. Shohet, "Stellarators," in Fusion, edited by Edward Teller (Academic Press, New York, 1981), Vol. 1, Part A, pp. 243-289.

FIGURES

FIG. 1. Schematic of a typical tokamak (PLT).

FIG. 2. The Tokamak Fusion Test Reactor, TFTR, in Princeton, shortly before first plasma operation.

FIG. 3. Schematic of a typical mirror (TMX).

FIG. 4. Schematic of Eino Bumpy Torus (EBT-1).

FIG. 5. Schematic of a typical reversed-field pinch (ZT-40).

FIG. 6. Schematic of a typical stellarator (Heliotron E).

Fig. 1

Fig. 2

Fig. 3

FIG. 4

278 cm MAJOR DIAM

40 cm MINOR DIAM

Fig. 5

Fig. 6

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20

Plasma Res Lab, Austr Nat'l Univ, AUSTRALIA
 Dr. Frank J. Poole, Univ of Wollongong, AUSTRALIA
 Prof. J.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cop, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Peumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakaneke, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hennes Bernard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
 Zhengwu Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, SW Inst Physics, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-696, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Muel, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. A.K. Sunderam, Physical Research Lab, INDIA
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indra, Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chavda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Merg, INDIA
 B. Buti, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Energy, KOREA
 Dr. R. England, Ciudad Universitaria, MEXICO
 Bibliotheek, Fom-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Dr. Surash C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Cabral, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALI CUZA University, ROMANIA
 Dr. R. Jones, Nat'l Univ Singapore, SINGAPORE
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Dr. J.A. Tagle, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Weise, Nat'l Bur Stand, USA
 Dr. W.M. Stacey, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Mr. Norman L. Oleson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Magne Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Taldak, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. M.S. Rabinovich, Lebedev Physical Inst, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. H.J. Keepler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmeforschung, W. GERMANY