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THE STELLARATOR APPROACH TO TOROIDAL PLASMA CONFINEMENT

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ABSTRACT

An overview is presented of the development and current status of the stellarator approach to controlled thermonuclear confinement. Recent experimental, theoretical, and systems developments have made this concept a viable option for the evolution of the toroidal confinement program. Some experimental study of specific problems associated with departure from two-dimensional symmetry must be undertaken before the full advantages and opportunities of steady-state, net-current-free operation can be realized.

I. INTRODUCTION

When one considers ways of confining a thermonuclear plasma, a toroidal solenoidal magnetic field is an obvious possibility. That such a simple field would not work can be seen immediately from the fact that its nonuniformity causes charge separation by the oppositely flowing $\mathbf{B} \times \nabla B$ drifts of the ions and electrons. This separation would create electric fields and the consequent $\mathbf{E} \times \mathbf{B}$ drift would move the plasma across the field lines to the outside of the system. This charge-separation problem can be solved by twisting the magnetic field lines, giving them a poloidal rotation as they go around the torus toroidally. The field lines then connect regions where positive electric charge would tend to accumulate to regions where there is a deficiency and the electrons can flow freely along the magnetic lines and neutralize the charge accumulations. A magnetic field line when followed many times around the system maps a toroidal surface which is called a magnetic surface. The average twist or rotation of the magnetic field line in this surface is the rotational transform and its rate of change between the magnetic surfaces is the magnetic shear. These quantities strongly affect the equilibrium, stability, and transport properties of the configuration. Tokamaks and reversed-field pinches obtain their rotational transform by means of a large toroidal current in the plasma, the magnetic field of which twists the magnetic field lines helically (see Fig. 1A). For reactor application, there are major engineering and physics problems associated with establishing these currents as well as transferring and storing the energy. Thermal stresses, if pulsed operation is contemplated, or providing provisions for radio-frequency or neutral-atom-beam current drive for steady state introduce further complications. A related problem is to control possible instabilities and

disruptions driven by the $LI^2/2$ free-energy reservoir available to distort the plasma.

An alternative approach is to create the poloidal fields, that are needed to twist the magnetic field lines, by means other than a force-free current inside the plasma. The twisting can be accomplished by mounting the coils that provide the magnetic field so that the coil centers lie on a nonplanar curve (Fig. 1B). Then the torsion of the magnetic field lines provides a rotational transform. Such a device can be visualized by imagining a line that encircles a doughnut-shaped surface one or more times before closing on itself. The simplest possible such curve, a figure-eight, defined the geometry of the original stellarator configuration. The much more recent Asperator device, now being studied in Sendai, Japan, is one where the doughnut is encircled several times. In both of these systems, the rotational transform is nearly the same on all the magnetic surfaces. Thus these geometries have little magnetic shear. It was recognized early in the development of stellarators that the need to control instabilities, where the plasma can expand into regions of weaker magnetic field by interchanging magnetic field lines, would make magnetic shear desirable. Shear can be obtained by placing ℓ pairs of helical windings, with current going in opposite directions in adjacent windings, inside the solenoidal field coils. Since these windings provide a rotational transform, there is no need for a nonplanar axis. The term "classical stellarator" is usually used for a system with this type of helical windings and a circular axis (Fig. 1C). A magnetic configuration with similar properties can also be obtained with a single set of ℓ helical coils, all carrying current in the same direction and an auxiliary poloidal field, or vertical field, coil. In this case, the helical coils twist around the magnetic axis and can provide

the toroidal field as well as the poloidal field. This system would be simpler to build than a classical stellarator and is called a torsatron (Fig. 1D). The heliotron approach has evolved into this same configuration. In the last few years it has been shown that a equate rotational transforms can also be obtained in systems with only a single set of discrete poloidal coils. These modular coils are di:·ortej from planar, much like the yin-yang coils used in mirror confinement, with the poloidal angle rotated between consecutive coils. This modular stellarator approach appears to simplify the engineering problems significantly.

These configurations look quite different from each other, and there has been a tendency to consider each one as something separate. On the other hand, the physical plasma behavior observed in, and the understanding that can be obtained from, any one of them is common to the others, and it is useful to recognize them all as members of the stellarator family. The accepted definition of a stellarator is that it is a closed, steady-state toroidal device for containing a hot plasma in a magnetic field where the rotational transform is produced externally, from torsion or from helical or modular coils outside the plasma.

It has been noted that the stellarator approach provides a solution to the difficulties stemming from the large toroidal ohmic-heating currents in tokamak plasmas. A price must be paid for this improvement; namely, one loses axisymmetry. A stellarator must be a three-dimensional system with no ignorable coordinate. This feature introduces new questions. Extensive theoretical and experimental efforts have contributed much to our understanding, but we still do not know how serious the problems introduced by this loss of symmetry are. The loss of symmetry complicates the shapes and quality of the magnetic surfaces, modulates the magnitude of the

magnetic field as one moves along a field line, and causes some particles to be trapped in the combined magnetic wells associated with toroidal and helical field line curvature. The convoluted orbits of these particles can lead to enhanced transport and particle loss. Further investigation of these effects is needed to ascertain how well stellarators will serve as fusion reactors. Favorable results could make them the device towards which a tokamak should evolve. In any event, progress on stellarators and tokamaks has always been very complementary and work on the two approaches is mutually supportive.

An introduction to the early stellarator work can be found in Bishop's book.[1] A review of the basic MHD equilibrium and stability considerations was prepared by Greene and Johnson.[2] A comprehensive analysis of the results obtained on the Model C Stellarator was given by Young.[3] Miyamoto's excellent review paper[4] summarizes the recent work well. Since it contains an extensive list of references, no attempt is made in this overview paper to refer to all the original work or to provide completeness. An informal history of the development of the stellarator program, based strongly on the material reported at the series of International Atomic Energy Agency Conferences on Plasma Physics and Controlled Nuclear Fusion Research, has been prepared.[5] Other reviews have been given by Shohet[6] and Rabinovich.[7] The flavor of the stellarator program was caught well in Shafranov's recent anniversary paper[8] in Nuclear Fusion. A joint U. S. - Euratom Stellarator Steering Committee has prepared a report[9] on the status and future directions for stellarator research. Much of the material in this overview is based on this report.

Lyman Spitzer, Professor of Astrophysics at Princeton University, introduced the stellarator concept in 1951 by proposing a figure-eight

device.[10,11] Work on stellarators was done in the 1950's only at Princeton. Several small stellarators were built in this period, and a reactor study[12] was completed.

On the theoretical front, the concepts of magnetic surfaces, magnetohydrodynamic equilibrium, and single particle confinement were developed.[11,13] Energy principles were derived[14,15] for stability studies.[11,16,17] This work indicated that the figure-eight stellarator, as it was then visualized, would be unstable and led to the idea that shear in the magnetic field lines would be needed to provide stabilization. The classical stellarator was therefore developed.[11,17] Studies of plasma formation, ohmic heating[18], and various forms of magnetic pumping[19] including ion-cyclotron-resonance heating[20] were analyzed.

Significant experimental progress was also made. Ohmically heated discharges[21] and the nature of the run-away electrons[22] in low-density plasmas were studied. The Kruskal-Shafranov stability limit was verified.[16] Relatively poor confinement was found, which was believed to be due to the presence of many impurities. A divertor[23] showed good improvement in impurity control, and effective ion-cyclotron-resonance heating was demonstrated.[24] It was realized by late in the decade that atomic and surface physics problems were dominating the plasma behavior so that the larger Model C Stellarator was commissioned.

Several groups entered the program in the 1960's. The Max-Planck Institüt at Munich (later Garching) and the P. N. Lebedev Physics Institute in Moscow were sufficiently impressed by the results reported at the Second United Nations Conference on the Peaceful Uses of Atomic Energy in Geneva in 1958 that they began their own programs. The successes of the Lebedev program prompted the Culham Laboratory to get involved. The

Institute of Physics and Technology of the Ukrainian Academy of Sciences at Kharkov entered the program, and a small stellarator was built at Novosibirsk.

Theoretical studies included the evolution of stellarator expansion techniques[25,26] to study magnetohydrodynamic equilibrium and stability, an effort to obtain systems with a minimum average magnetic field to circumvent resistive instabilities,[27-31] and the development of neoclassical transport theory.[32-37] This theory showed that confinement would be impaired in collisionless plasmas even in axisymmetric systems by the large drift orbits of the particles trapped in the magnetic well created by the inhomogeneity of the toroidal field. It indicated that the much larger "superbanana" orbits of particles trapped in the combined helical and toroidal wells in three-dimensional systems would be disastrous. It appeared that large bootstrap currents would be driven by these neoclassical mechanisms[38,39] leading to kink instabilities. Problems associated with magnetic islands and magnetic field line ergodization were discussed.[40-43]

Experimental work continued without providing a clear understanding of stellarator behavior. Particle confinement in the Princeton devices was discouraging, with Bohm-type diffusion, $\tau \propto B/T$, observed.[3] On the other hand, neoclassical confinement was observed with cesium plasmas at Garching[44,45] and with gun-injected plasmas at Lebedev[46] and Culham.[47,48] Radio-frequency heating with $T_i \sim 400$ eV was obtained in the Model C Stellarator.[3]

The combination of discouraging containment times on the Model C Stellarator, the theoretical predictions of the transport losses becoming even worse as the collisionless regime is approached, and the difficulties envisioned with engineering complexity and reactor design dampened the

spirits of the investigators. Thus, when high temperatures were reported on the T-3 tokamak at Kurchatov,[49] the decision to convert the Model C Stellarator into the ST Tokamak and abandon stellarator research in the United States was welcomed by many. Good results were found on this new tokamak, and further work with this and later devices has demonstrated the viability of toroidal confinement. A possible explanation for the poor confinement in the Model C Stellarator is that the useful aperture was more limited by magnetic islands and poor magnetic surfaces than was believed while research was being done.[42]

The decade of the 1970's saw increased activity in Europe and Japan. Fairly early in this period the PROTO-CLEO stellarator was moved from Culham to the University of Wisconsin so that a United States program was established again. The heliotron at Kyoto, based on a desire to have a magnetic separatrix inside the vacuum vessel, acquired a rotational transform,[50] and the torsatron[51] was devised to simplify stellarator construction. Many experiments were conducted on radio-frequency[52-54] and turbulently heated discharges.[55,56] Much work was done on the study of magnetic surface resonances[55,57] and plasma confinement.[58] Towards the end of the decade it had been established reasonably well[56-59] that stellarator confinement is as good as or better than that in an equivalent tokamak, that confinement improves with decreasing net ohmic heating current, and that an externally imposed rotational transform can be used to prevent disruptive instabilities.

Several recent developments have created worldwide excitement for the stellarator concept. Net-current-free plasmas with impressive plasma parameters and good energy containment have been confined in WENDELSTEIN VII-A[60] and HELIOTRON E.[61] Monte-Carlo studies[62-65] indicate that

neoclassical transport may be less restrictive than had been thought. New ideas concerning modular coils[66-69] appear to simplify the engineering. The stellarator concept has become a very logical direction towards which the tokamak can evolve.

II. EXPERIMENT

The major stellarator facilities, operating in the past few years, include CLEO at Culham (operation of which was recently terminated), L-2 at the Lebedev Institute, JIPP T-2 at Nagoya (which will probably be operated primarily as a tokamak in the future), and WENDELSTEIN VII-A at Garching. These were joined recently by HELIOTRON E at Kyoto. The URAGAN-III torsatron at Kharkov should soon become operational. The results from these machines were summarized recently[70] and are contained in the report of the U. S. - Euratom Stellarator Steering Committee.[9] These devices are quite different, with WENDELSTEIN VII-A and JIPP T-2 having low shear and moderate rotational transform, CLEO and L-2 more shear and transform, HELIOTRON E high shear and transform, and URAGAN III strong shear and moderate transform. Their machine parameters are given in Table I. WENDELSTEIN VII-A and HELIOTRON E, which are expected to make the most contributions in the near future are shown in Figs. 2 and 3.

II.A. Discharges with Ohmic-Heating Current

Since ohmic currents provide an easy and efficient way to heat a plasma, studies of ohmically heated plasmas have characterized all the stellarator programs. The basic results, especially for small externally applied rotational transforms, are not dramatically different from tokamaks. Although the geometries of the various stellarators are quite

different, the results are surprisingly similar.

Kink and tearing modes are usually found when the current is at or near specific values where the rotational transform has low-order rationality. They produce the usual growth of magnetic islands. Over the years this type of behavior has been studied through measurements of the distortion of the magnetic surfaces[71] as well as by observing changes in energy confinement.

Figure 4, which shows the change in the electron energy confinement time as a function of the ohmic heating current with the externally applied transform fixed, in the CLEO device[9,72] is typical of this type of study. Similar work on other devices shows a correlation of these increases in transport at rational transforms to magnetic field fluctuations at the rational surfaces. A typical energy containment study is given in Fig. 5, which was obtained on JIPP T-2.[73] An inverse scaling with the ohmic heating current is observed. The fall-off at low current can be explained by the degradation of the plasma due to lack of energy input. Considerable effort has been expended in studying the parametric dependence of the electron thermal conductivity. The Garching work has led to an empirical scaling[9,74]

$$\chi_e \sim I_p/BnT^{1/2} \quad , \tag{1}$$

which is close to drift parameter scaling. Note that the behavior of Fig. 5 is in good agreement with this.

A major difference between stellarator operation and tokamak behavior is the suppression of major disruptions with an externally applied rotational transform. A critical transform, $\iota_H > 0.14$, was observed on both JIPP T-2[73] and WENDELSTEIN VII-A.[74] This is believed to be due to keeping the $\iota = 0.5$ rational surface outside the plasma although it may be

associated with the increased rigidity of the field.

Operation with the total rotational transform $\iota(a) \sim 2.5$, well above the Kruskal-Shafranov limit, is obtained in *HELIOTRON* E,[75] in agreement with theoretical predictions.[76] Very respectable plasma parameters, $n \sim 2 \times 10^{19}\ m^{-3}$, $T_e \sim 1$ keV, $\tau_E \sim 10$ msec, $I_p \sim 100$ kA and $B \approx 20$ kG, were found on that device.[75]

One can conclude that for discharges with low beta the incorporation of a helical field into a tokamak is beneficial. The degradation of symmetry may become important as beta, the ratio of material to magnetic pressure, is increased.

II.B. Ohmic Plasmas with Auxiliary Heating

Stellarator studies with pure ohmic heating show that confinement improves with decreasing current but that the decrease in ohmic heating power narrows the accessible parameter range. Auxiliary heating must be introduced to get to lower currents. It has been achieved with lower hybrid radio-frequency heating and neutral-atom-beam injection.

Lower-hybrid studies in JIPP T-2[73] show similar ion temperature heating rates, ~1 eV/kW, for operation in both the stellarator and tokamak modes. At high power, there is a reduction of heating efficiency if $\iota_H(0) > 0.14$ which may be due to a loss of fast ions due to the helical ripples.

Neutral injection has been studied in WENDELSTEIN VII-A,[60] JIPP T-2,[73] and CLEO.[77] The heating efficiency was relatively low in each case, which could be understood in terms of direct orbit losses of the injected particles. Improvement of plasma properties was observed. The increase in density that can be confined stably in CLEO, above that with only ohmic

heating, is shown in Fig. 6 and is typical.

II.C. Net-Current-Free Operation

Much work has been done on current-free confinement of low-density, low-temperature plasmas in many devices. These experiments were summarized well by Miyamoto.[4] Lack of electron-cyclotron-resonance-heating or neutral-atom-beam power and difficulties in obtaining a sufficiently dense, currentless target plasma prevented operation with interesting plasma parameters. Problems with diagnostics and the analysis of plasma parameters further complicated interpretation of the results.

The recent achievements with net-current-free-operation in WENDELSTEIN VII-A[60] and HELIOTRON E[61] have been major factors in the rebirth of interest in stellarator physics. The improvement in confinement with decreasing ohmic current, shown in Fig. 5, suggests that pure stellarator operation should be optimum. As can be seen from Fig. 7, this is indeed the case.

The availability of high-power neutral beams made net-current-free operation with interesting plasma parameters possible in WENDELSTEIN VII-A.[60] It was necessary to use ohmic heating to create a target plasma. As can be seen in Fig. 8, the plasma current is turned off during the injection, with the helical fields increased to maintain a constant total rotational transform. If the transform at the magnetic surface is less than 0.5 so that $q = \iota^{-1} = 2$ rational surface is inside the plasma and tearing modes or disruptions should occur, the plasma pressure is severely limited. For transforms above 0.5 significant plasma parameters, $T_i \sim 700$ eV, $T_e \sim 500$ eV, $n \sim 10^{20} m^{-3}$, together with a strong reduction in fluctuation level and vanishing of the magnetohydrodynamic activity, are obtained. The measured energy containment time is about 5 to

8 msec. Correction for radiation associated with the plasma impurity would lead to $\tau_E \sim 35$ msec. For the confinement time to be shorter, it would be necessary that more of the beam be captured than was predicted by the theoretical calculations. Thus, these containment times are better than what would be expected from extrapolation of tokamak experience.

Two hundred kW electron-cyclotron-resonance-heating power was applied to HELIOTRON E, with 80 kW absorbed, to produce a net-current-free plasma.[61] The behavior is shown in Fig. 9. The electrons, with a density of $5 \times 10^{18} m^{-3}$, approach temperatures of 500 eV. When the heating is turned off, they equilibrate quickly with the ions so that $T_e \sim 200$ eV, and $T_i \sim 150$ eV. Then, the plasma decays with $\tau_E \sim 40$ msec. Neoclassical confinement of both the ion and the electrons is claimed.

III. THEORY

Recent developments in theoretical techniques and results have complemented these experimental achievements. Most of the work has occurred in the areas of magnetohydrodynamic equilibrium and stability and of individual particle confinement and transport. Much more theoretical work on these problems is needed. It should be recognized that the calculations will at best indicate the nature of the physics, and the final answers will come only from experiment.

III.A. Equilibrium and Stability

Since stellarator magnetic fields are complicated, much of the effort has utilized simple magnetohydrodynamic models. It is difficult to justify the use of these models rigorously except in collisional regimes that are

not relevant to reacting plasmas. Nevertheless, it has been found that they describe the macroscopic behavior of confined plasmas very well.

The equilibrium problem is the determination of solutions of

$$\underset{\sim}{J} \times \underset{\sim}{B} = \nabla p \quad , \qquad \underset{\sim}{J} = \nabla \times \underset{\sim}{B} \quad , \qquad \nabla \cdot \underset{\sim}{B} = 0 \quad , \tag{2}$$

with the magnetic field lines forming useful magnetic surfaces.[13] The plasma behavior can be understood from the condition that the current be divergence free, which can be written as

$$\underset{\sim}{B} \cdot \nabla(\underset{\sim}{J} \cdot \underset{\sim}{B}/B^2) = 2\underset{\sim}{B} \times \nabla p \cdot \underset{\sim}{\kappa}/B^2 \quad , \tag{3}$$

with $\underset{\sim}{\kappa}$ the local curvature of the magnetic field lines. This merely says that currents must flow along the field lines to cancel the charge separation which arises from particle drifts associated with curvature of the magnetic field. The secondary currents which arise from this move the magnetic surfaces outward in typical stellarators just as in tokamaks. This shift imposes limits on the achievable beta, but it also provides an "average magnetic well" for plasma stability. Comparison of stellarator and tokamak equilibria using Eq. (3) exhibits two differences. The $\underset{\sim}{B} \cdot \nabla$ operator on the left-hand side of the equation contains a contribution from the externally applied rotational transform. Similarly, the curvature $\underset{\sim}{\kappa}$ contains an additional contribution due to the nonaxisymmetric fields. Another difference, which cannot be seen from this equation, is the increase in island structure and ergodicity due to nonlinear resonances of the magnetic field lines in asymmetrical configurations.

It is not too difficult to get a rough expression for an equilibrium

limitation on beta from Eq. (3), similar to that for a tokamak. If one assumes a nearly axisymmetric configuration, averaging over the helical bumps, it follows that the parallel current is roughly proportional to $2(dp/dr)\cos\theta/\kappa B$, and is nearly toroidal. This current sets up a vertical field. The magnetic axis is shifted outward by this field. At the same time, a separatrix approaches the plasma from the inside of the torus at the position where this field is roughly $\kappa r B/R$. Keeping this separatrix outside the plasma, as well as restricting the shift of the magnetic axis, provides a limit on beta, $\beta \lesssim \kappa^2 a/R$. This restriction could be adjusted by properly shaping the externally applied vertical field.

It is also useful to note that if the right-hand side of Eq. (3) can be made to vanish, no secondary currents will be driven. This can be done[25] by making $\int d\ell/B$, evaluated over some periodicity length along a magnetic field line, independent of the position on a magnetic surface. Minimization of the variation of this function, subject to some constraints imposed by stability considerations as well as technology, has formed the basis for the most ambitious optimization program[78,79] that has yet been undertaken for stellarator design.

To understand the stability problem, it is useful to write δW, the change in potential energy of the system with respect to an arbitrary fluid displacement $\underset{\sim}{\xi}$ from equilibrium, in the form[80]

$$2\delta W = \int d\tau \, \{Q_\perp^2 + B^2(\nabla\cdot\underset{\sim}{\xi}_\perp + 2\underset{\sim}{\xi}\cdot\underset{\sim}{\kappa})^2 + \gamma p(\nabla\cdot\underset{\sim}{\xi})^2 + \underset{\sim}{J}_\parallel \times \underset{\sim}{\xi}_\perp\cdot\underset{\sim}{Q}_\perp$$

$$- 2\underset{\sim}{\xi}_\perp\cdot\nabla p\,\xi_\perp\cdot\underset{\sim}{\kappa}\} \quad ;$$

$$\underset{\sim}{Q} = \nabla \times (\underset{\sim}{\xi}_\perp \times \underset{\sim}{B}) \quad , \qquad (4)$$

is the perturbed magnetic field. The first term can be associated with shear Alfvén waves. The next two terms represent the magnetosonic branches with $B\nabla\cdot\xi_\perp$ the local compression of the magnetic field. If $\nabla\cdot\boldsymbol{\xi}_\perp \approx 0$, the third term is the slow wave or acoustic branch. The fourth term is the change of energy associated with the interaction of the force-free currents with the perturbed magnetic field. It drives kink and tearing instabilities. The last term is the energy associated with expansion or compression of the plasma and is responsible for interchange and ballooning modes. Stellarator stability studies usually find that the most unstable modes have $\nabla\cdot\boldsymbol{\xi}_\perp \approx \nabla\cdot\boldsymbol{\xi} = 0$ to eliminate the magnetosonic branches. It is often argued (and can be demonstrated for specific cases) that, if there is no net current, the kinking term affects the growth rate and shape of the unstable perturbations but does not modify the criterion for the onset of instability. Thus, balancing the stabilization due to bending the magnetic field lines against the expansion energy determines the stability criterion for a net-current-free stellarator. Having some average magnetic well and reasonable connection length, or large shear, to control pressure driven modes is all that is needed.

A rough stability criterion can be obtained from Eq. (4). If (as in a typical torsatron or heliotron) the configuration has no magnetic well, one can estimate the expansion energy as approximately $2\xi^2 p \langle B_\delta^2\rangle/a^2B^2$ with $\langle B_\delta^2\rangle$ the average field associated with the helical structure and B^2 the toroidal field component. This must balance the shear energy $\iota'^2(r - r_o)^2B^2\xi'^2 \approx \iota'^2B^2\xi^2/4$ due to twisting field lines. Thus, $\beta \lesssim \iota'^2a^2B^2/4\langle B_\delta^2\rangle \propto \langle B_\delta^2\rangle/B^2$ since the transform and shear are associated with $\langle B_\delta^2\rangle/B^2$. It can be seen from this that large shear is desirable. If

the equilibrium shift of the plasma associated with Eq. (3) is large enough to dig a magnetic well, then the length entering the $\underset{\sim}{B}\cdot\nabla$ expression in the first term of Eq. (4) must be the connection length R/χ, and the dominant curvature effect in the last term is $1/R$. Equating these leads to $\beta \sim \chi^2 a/R$, similar to the equilibrium limitation.

III.A.1. Techniques

An extensive formalism has been developed to use the "stellarator expansion," essentially a large-aspect-ratio expansion where the distortions from axisymmetry are assumed to be small and periodic over a length which is short compared to the major radius of the system.[17,25] Then, averaging over this periodicity length reduces the equilibrium problem to a straightforward generalization of the Grad-Shafranov tokamak equation[25] which can be solved either numerically or with the introduction of an auxiliary expansion. As was already noted, this same expansion eliminates the magnetosonic branches from the stability problem so that it too is manageable.[26,81]

A second approach that has also provided significant insight is to make an expansion about a closed magnetic field line, typically the magnetic axis.[82-84] This technique provides a useful local stability criterion. It also provides a formalism for discussion of the properties of equilibria where the shapes of the magnetic axis and of the inner magnetic surfaces are prescribed. The method has been applied to many specific configurations where it has been found that large-aspect-ratio systems with good equilibrium and stability properties exist.

Computer hardware is just now capable of handling three-dimensional equilibrium computations. Two major codes have been written for this purpose.[85,86] Although the techniques are different, both basically

minimize the potential energy functional

$$W = \int d\tau \, [B^2/2 + p/(\gamma - 1)] \quad . \tag{5}$$

Some indication of the stability properties can be obtained by investigating the relaxation with additional constraints.[87]

III.A.2. Applications

Although all of these approaches have been used to obtain a qualitative understanding of stellarator behavior and even to investigate properties of special configurations, general application of them to develop specific machine designs has been made only recently. In the most extensive study,[78,79] it was argued that the vacuum magnetic field should be shaped to reduce the force-free currents of Eq. (3) as much as possible, consistent with the magnetic field possessing a small average magnetic well to assure stability with respect to interchange modes. This should eliminate restrictions arising from equilibrium considerations on the pressure that can be confined. At the same time, it ensures good confinement of the circulating particles. The program was started from the understanding that combinations of helical magnetic fields with different helicities can minimize the variation of $\int d\ell/B$, evaluated over one periodicity length, on a magnetic surface and thus the secondary current. Variational techniques were used to optimize the choice of a set of harmonic functions which minimized this $\int d\ell/B$ variation, subject to imposition of constraints concerning magnitudes of the rotational transform, presence of a magnetic well, etc. Coils which could generate these fields were then found by assuming that the fields were due to surface currents in a shell outside the

plasma and replacing them with currents in discrete coils. The magnetic fields were then recomputed and the three-dimensional numerical program applied to verify the equilibrium properties. Critical betas of ten percent or more were obtained.

Most other analyses have utilized localized criteria.[88,89] Some understanding of properties of macroscopic modes can be obtained from numerical calculations.[87] These also lead to critical betas between four and ten percent for realistic geometries.

III.B. Transport

It was noted earlier that predictions of enhanced diffusion and energy transport in collisionless plasmas due to the large superbanana orbits of trapped particles[32–37] are very pessimistic. These calculations used estimates of the number f of particles trapped in the different wells and the size Δr of the drift orbits of these particles to estimate the diffusion by means of a random-walk model,

$$D \sim f(\Delta r)^2 \nu \quad , \tag{6}$$

for a given collision frequency ν. It was recognized that changes of any of these functions due to the presence of an ambipolar electric field, the departure of the field structure from the simple calculational models, etc., would modify the diffusion, but it was generally believed that the magnitude could not be changed very much. Recent Monte-Carlo transport studies[62–65] indicate that more realistic models may provide somewhat better results.

Individual particle confinement and transport studies use particle orbits that are usually calculated with guiding-center drift equations.

Confinement studies[90] show that, at least if the aspect ratio of the system is greater than ten, most of the high energy particles, including 3.5 MeV alphas, can be confined long enough that they can give their energy to the plasma rather than carry it out of the system.

Monte-Carlo treatments of transport can be performed[63] by choosing an ensemble of particles on a particular magnetic surface with the same energy but with different initial pitch angle. By subjecting these to random Lorentz collisions, the diffusion function $D(E, \phi)$ can be deduced. Integration over energy leads to expressions for particle and energy transport coefficients.

Calculations using the actual vacuum magnetic fields of a proposed torsatron reactor[62] showed no sign of the $1/\nu$ collisionality dependence which had been expected, as can be seen in Fig. 10. Results for a model stellarator field,[63] Fig. 11, showed some enhanced diffusion in the superbanana regime, with the magnitude a factor of ten worse than in an equivalent tokamak but much less than would have been predicted by the models used in the original calculations of neoclassical transport in stellarators.[38] Since this is an order of magnitude better than what is actually observed in tokamak operation where the electron transport is anomalously large, these results seem quite optimistic. Somewhat more pessimistic numbers have been obtained elsewhere.[91]

Mynick[64] has made a detailed study of the behavior of the individual particles in these calculations. He finds that the predicted loss estimates are well reproduced for the simple model fields used in the earlier analytic treatments.[36] Much of the improvement in the recent models is probably due to the more complicated magnetic field structure. The particles appear to spend much less time in the trapped regions than one would have expected

since the ripples tend to lose their identities in these complicated fields. Thus, the trapped particle fraction f should be reduced in Eq. (6). Furthermore, the major contribution to the loss arises from very high energy particles, with energies greater than five times the thermal energy. Exploratory studies have indicated that only a small fraction of these particles with specific values of $v_\parallel/v_\perp$ are responsible, and that the rate of refilling this part of velocity space is small.

The transport picture must be summarized as one with considerable uncertainty, but there is good justification for the optimism that pervades the stellarator community. What has emerged is the understanding that transport is very sensitive to the specific details of the device and the nature of the ambipolar electric fields set up in the plasma. Although theoretical work on this subject should be expanded, experimental investigation with several types of magnetic fields seems necessary.

III.C. Bootstrap Current

A major unresolved stellarator problem concerns the existence and magnitude of the diffusion-driven, force-free current—the bootstrap current. This is theoretically predicted to occur in the collisionless regime[38,39] due to the radial variation in the density of banana-trapped particles. Since this current can be identified with momentum conservation in two-dimensional systems like tokamaks, it is not clear what form it will take in stellarators. If it were as large as estimates based on superbanana transport predict, it would impose stringent limits on the plasma beta. It should have been observed in Proto-Cleo, but was not seen.[92] Experimental investigation of this problem is needed.

Estimates of the magnitude of this bootstrap current are based on an

axisymmetric model and lead to a value of the order of $J_\phi \approx (dp/dr)/[(r/R)^{1/2} \iota B]$.[4,39,93] Since this current can drive a kink instability, the condition that the total transform be less than one restricts beta to a small value. Indeed, in the most recent reactor study that has been carried out[94,95], the average beta was limited four percent by this bootstrap current.

IV. SYSTEMS STUDIES

The stellarator was one of the first magnetic fusion energy approaches for which a systems study was made to investigate its reactor potential. The Princeton Model-D design[12] is still one of the most comprehensive extrapolations of a confinement concept to the reactor stage. This study used the untenable assumption that an average beta of 0.75 could be confined. The next major stellarator reactor study was made at Culham.[93,96] The severe limitations associated with the low values of beta, which were imposed by conservative equilibrium and transport considerations, resulted in the need for systems with large magnetic field strengths in the inner sides of the coils. This, together with the complexity of the coil configuration and the problems of supporting the coils against the large magnetic forces, which in some places were directed towards the plasma, appeared to pose insurmountable problems for stellarators.

The torsatron concept drastically simplified the problems associated with the coil forces. The HELIOTRON-C design[97] was based on a large beta value and a large major radius. Like the earlier stellarator models, it had a large power output. The Kharkov torsatron design[98] also has a large power output. The T-1 design study at the Massachusetts Institute of Technology[99] showed that this approach has considerable promise.

Recent developments in this area include the evolution of modular stellarator coils which provide another way to solve the force problems.[66-69] The use of these coils provides an attractive approach for reactor design. Studies of modular stellarators at Los Alamos[94,95] and at Wisconsin[100] are encouraging. The nature of these modular coils, some aspects of the divertor-limiter problem, and an outline of the latest reactor studies will be reviewed in the remainder of this section.

IV.A. Modular Coil Optimization

Modular stellarator coils were first suggested by Rekher and Wobig[101,102] who introduced a coil winding law

$$\phi = \phi_j + \frac{d}{R} \sin (\ell\theta - \theta_j) \quad , r = a. \qquad j = 1, 2, \ldots N \ . \tag{7}$$

Here $\phi_j = 2\pi j/N$ is the toroidal position of the j^{th} coil, $\theta_j = 2\pi m j/N$ is the poloidal phase angle of this coil, ℓ and m are the poloidal and toroidal mode numbers, N is the number of coils, and a is the coil radius. These discrete, deformed, and rotated toroidal field coils, Fig. 12, provide the entire magnetic field needed for stellarator operation. This approach was not generally adopted because only small rotational transforms could be obtained without introducing large coil distortions.

It was recently recognized that improvement could be achieved by introducing higher harmonics in the coil winding.[68] One way of looking at this is to visualize the coils as representing a set of opposing torsatron windings with different pitches. A device based on this principle has been constructed.[67] A useful way of understanding how to optimize the coil shape is to study how a careful tailoring of the coil deformation changes the

harmonic content of the magnetic field generated by the coil. Such an investigation[68] shows that the field is strongly dependent on the exact shape of the coil near the points where $\ell\theta - \theta_j = 0$ or π. in Eq. (7). By providing additional shaping in this region, the harmonic content of the magnetic field can be adjusted so that relatively small distortions can provide an adequate rotational transform. Plasma properties in these magnetic fields are being investigated[103]. The coils are quite similar to the "yin-yang" coils[104] that have already been constructed for the mirror program.

IV.B. Divertors and Impurity Control

Since a stellarator is a steady-state device, the nature of the interaction of the plasma with the outside world is especially important. Thus fueling and impurity control and exhaust need special attention. To a large extent, these problems are similar to those encountered in a tokamak, which requires long-pulse operation. Most of the solutions developed and envisaged for that device can be applied to stellarators. One possible difficulty that may be different is that impurities may accumulate in the center of the plasma. The sawtooth oscillations, associated with internal kink instabilities, may prevent this from occuring in tokamaks. Since stellarators are intrinsically more stable, there may be a need for auxiliary control.

One exciting stellarator feature is that a separatrix, or magnetic limiter, is built into the magnetic field automatically, and there is no need for additional coils. This is particularly true for torsatrons. The favorable reactor study results[97,99,105] for this device were strongly dependent on this feature. An exciting development in the study of modular

coils has been that divertor action can be obtained.[69] The efficacy of this approach is demonstrated in Fig. 13. Here the magnetic structure of the modular divertor region was studied by tracing the magnetic field lines which link the scrape-off region with the exterior of the torus. These lines were distributed uniformly over a thin layer bounded on the inside by the surface containing the magnetic separatrix and were followed until they emerged between the coils. The left-hand figure shows the intersections of all these lines with a cross section directly under a coil. The right-hand figure is at a position between coils. Mappings made for a number of poloidal cross sections can provide a detailed picture of the divertor structure. The Wisconsin reactor study[100] incorporates this type of divertor as a major design constraint.

A pumped limiter can be used for plasma exhaust in a stellarator, just as in a tokamak. The main advantage that could be gained by using it would be better utilization of the volume inside the coils. The Los Alamos reactor design[94,95] has adopted this approach.

IV.C. Recent Reactor Studies

In the last few years, four different reactor studies with different degrees of sophistication have been started. Two[97,99,105] of these have treated the torsatron approach; the other two[94,95,100] assumed construction with modular stellarator coils. This brief review was taken from the U. S. - Euratom study.[9]

IV.C.1. Massachusetts Institute of Technology, T-1 Design[99]

A reactor design has been completed using a steady-state, moderate-aspect-ratio, neutral-atom-beam-ignited, $\ell = 3$ torsatron with continuous

helical windings in a nearly force-free configuration and a natural divertor. Even with conservative engineering and physics assumptions, an economically interesting configuration of acceptable size was defined. The notable feature of the device is that modularity is achieved by having twenty identical units consisting of demountable coil segments containing the blanket and shield. The coil itself is superconductive, but the joints between the modules are resistive. The major reactor parameters are given in Table II.

IV.C.2. Kyoto University HELIOTRON Design[97,105]

A preconceptual design of an $\ell = 2$ heliotron with no toroidal coils and a built-in divertor has been carried out. The geometry is optimized to provide a large rotational transform and strong shear. For an estimated maximum beta of 0.1 to 0.2, the plasma should be in the plateau regime of neoclassical theory. The outstanding feature of this reactor is that it employs a breeding blanket only between the coils and can have a thinner shield to protect the coils. The effort and cost of coil construction and support is thus minimized by keeping them close to the plasma. Maintenance of the blanket is assured because of its easy accessibility, but the design has the disadvantage that the coil is virtually not maintainable. An extensive neutronic analysis has been carried out to assure stability of the structure and a positive tritium breeding ratio. A partial parameter list for this heliotron reactor is given in Table III.

IV.C.3. University of Wisconsin UWTOR-M[100]

The University of Wisconsin Fusion Engineering Group, in collaboration with the Stellarator/Torsatron Laboratory, has been examining some of the

engineering problems of modular stellarators. The aim is to produce a self-consistent reactor engineering design with good maintainability, while maximizing the prospects for favorable plasma physics conditions. The initial design contraints were coil modularity and a magnetic divertor topology. The main design goals were a high rotational transform and an effective magnetic volume utilization within a practical and maintainable coil system. An assumed β of 5% was used. The selected magnetic divertor together with an $\ell = 3$ multipolarity provides a large rotational transform. Several coil iterations led to the parameters listed in Table IV.

IV.C.4. Los Alamos National Laboratory MSR Study[94,95]

The initial work on the Modular Stellarator Reactor (MSR) study has focused on the development and evaluation of a simplified but general systems model that quantifies the relationship between the performance of the plasma (beta limits associated with equilibrium, stability, and transport constraints, power density, etc.), coil design (stresses, current density, etc.), and reactor considerations (wall loading, total power, accessibility, maintenance, etc.). Conservative assumptions led to the interim design parameters of Table V. The conclusion is that, even with pessimistic physics assumptions, an interesting reactor design can be achieved. These parameters should soon be the basis for a detailed conceptual engineering design to obtain an economic evaluation of this approach.

IV.D. Comparison With Other Systems

One must be impressed by the advances that have occurred in the last decade. The reasons for the pessimistic outlook for stellarators[93,96] reported at the time tokamaks were becoming the leading fusion candidate seem less severe, and the latest study[94,95] indicates that the approach is viable. Indeed, it has been shown that conservative physics assumptions lead to reactors with acceptable total power. The exerience gained in many years of stellarator operation, together wtih the insight that can be translated from tokamak studies, gives it a firmer physics foundation than that posessed by any other alternate fusion approach. As can be seen in Table VI[94,95,100,104], the two latest reactor studies lead to systems that compare well with that of the leading magnetic toroidal fusion design. In the Starfire study, the physics base could be strengthened, especially concerning the assumptions associated with the radio-frequency current drive needed for steady-state operation. Since the stellarator studies used more conservative physics assumptions, these comparisons must be viewed as encouraging.

V. PROBLEMS AND TASKS

As has been demonstrated by recent experimental, theoretical and systems-studies developments, the stellarator concept has emerged as a viable magnetic fusion energy approach. Indeed, these advances complement the favorable tokamak developments where useful plasma parameters and operation have been obtained, but where difficulties associated with the development of radio-frequency current generation and plasma disruptions remain to be solved in order to realize steady-state operation. Clearly, the stellarator approach can provide an obvious direction for tokamak evolution.

Some unaddressed physics problems must be introduced into the program for this type of change of emphasis in the toroidal fusion program to occur. These all concern the complications associated with the three-dimensional nature of the confining magnetic fields and will require both theoretical and experimental efforts.

The U. S. - Euratom Stellarator Steering Committee[9] grouped some of these important problems under several headings:

(i) investigate plasma transport properties in the collisionless, net-current-free regime, including a study of the presence and nature of diffusion-driven current;

(ii) investigate equilibrium and stability limitations on the critical beta, including a determination of how well reduction of secondary current by minimizing the variation of local contributions to $\int d\ell/B$ on a magnetic surface optimizes confinement;

(iii) investigate the nature of self-consistent electric fields and determine their effects on particle orbits and confinement and energy transport;

(iv) examine dependence on magnetic topology, obtaining an understanding of how confinement is affected by changing the magnitude of the rotational transform, shear, average magnetic well, harmonic content of the field, etc.;

(v) determine the mechanisms responsible for the release, transport, and control of impurities in these asymmetric systems;

(vi) determine the effects of asymmetry on wave propagation and develop efficient heating methods.

All of these problems have aspects that are significantly different from those of the tokamak program. Theoretical efforts can and will provide

some of the answers, but experimental input will be essential. Since these problems must be studied under reactor-relevant conditions, they will require devices capable of obtaining and confining a net-current-free, collisionless plasma with high temperature, reasonable density, and sufficient size that atomic and surface physics will not be important.

VI. CONCLUSIONS AND OPPORTUNITIES

Recent developments in experiment, theory, and systems studies make prospects good for the stellarator to resume its place as a viable reactor concept. Confinement of net-current-free plasmas with plasma temperature, pressure, and energy confinement times comparable to or better than equivalent tokamaks has been demonstrated on WENDELSTEIN VII-A using neutral injection[60] and on HELIOTRON E using electron-cyclotron-radio-frequency heating.[61] Monte-Carlo transport calculations[62-65] indicate that confinement can be much better in the collisionless regimes, if proper field configurations are used, than had been predicted earlier. The development of new modular coil shapes[66-68] has provided a solution to the engineering difficulties associated with complicated, interconnected coils. Even with conservative assumptions concerning plasma properties, very acceptable solutions to reactor design problems can be found.[94,95]

Stellarators have many similarities with tokamaks but, because of the absence of net currents in the plasma, they have a number of distinct and exciting properties:

(1) steady magnetic fields with nested magnetic surfaces which provide confinement from the initial ionization of the plasma and have the potential for steady-state operation without thermal cycling of the walls or need for energy transfer or storage or further external heating,

(ii) no major disruptions that could lead to an excessive energy dump on the wall;

(iii) moderate or large plasma and coil aspect ratios which provide improved access and have higher magnetic fields in the plasma for fixed field strengths at the inner legs of the coils than in a tokamak, allowing the same fusion power densities at lower values of beta;

(iv) simple modular design with only one set of coils needed to produce the full magnetic field and no need for feedback position control;

(v) several potential methods for impurity control and ash removal, including divertors and limiters.

There is general agreement that the scientific feasibility of toroidal magnetic confinement has been, or soon will be, demonstrated in tokamaks. The next step is to improve the pulse length so as to obtain a test bed for the development and demonstration of fusion-relevant technology. The tokamak should be able to do this.

At the same time that this engineering effort is getting underway, physics efforts towards optimization of reactor concepts should be undertaken. Development of the stellarator program should proceed logically to answer the relevant physics issues in the next few years so that its feasibility can be demonstrated before the optimum reactor concept is selected.

With this optimistic picture of stellarator opportunities, it is perhaps useful to speculate on what will take place in the next few years.

In the period after the first spectacular current-free operation of WENDELSTEIN VII-A, an effort has been made to improve the impurity content in the neutral beams as well as to extend the diagnostics so as to get a better accounting of where and how the energy is being introduced into the

plasma, confined, and lost. This type of work is slow and unrewarding, but very necessary. It is possible that some toroidal field coils will be removed to improve the injection angle of the beams. Much effort has gone into magnetic field optimization studies aimed at minimizing the secondary currents. These could lead to a proposal in the near future for an $\ell = 2$ modular coil stellarator, WENDELSTEIN VII-AS, which could test the efficacy of this approach.

Neutral injection is now becoming available on HELIOTRON E so that more than one technique for obtaining current-free plasmas can be used. This very flexible facility should provide significant answers to some important stellarator physics problems in the next few years.

We have little information concerning progress in the Soviet Union. URAGAN III, a large $\ell = 3$ torsatron, should soon become operable in Kharkov. It should be expected that this laboratory, the Kurchatov Laboratory and the Lebedev Institute will continue to provide leadership in stellarator research.

Stellarator activity in the United States has been small. There has recently been a rekindling of interest, and there is hope in the stellarator community that this will lead to the emergence of an active program. It appears that the ISX-C Tokamak being planned at the Oak Ridge National Laboratory will be changed to an Advanced Toroidal Facility on which some stellarator problems can be investigated. Since stellarators provide an obvious direction for the evolution of tokamaks as they are pushed towards steady-state operation, it is reasonable to expect movement in this direction.

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TABLE I. Stellarator Devices

	CLEO	L-2	JIPP T-2	WENDELSTEIN VII-A	HELIOTRON E	URAGAN III
Type	Classical Stellarator	Classical Stellarator	Classical Stellarator	Classical Stellarator	Heliotron	Torsatron
Winding	$\ell = 3$, $m = 7$	$\ell = 2$, $m = 14$	$\ell = 2$, $m = 4$	$\ell = 2$, $m = 5$	$\ell = 2$, $m = 19$	$\ell = 3$, $m = 9$
Field (T)	2	2	3	3.5	2 ± 0.6	3
R(m)	0.9	1.0	0.91	2.0	2.2	1.0
r(m)	0.1	0.11	0.17	0.1 (noncircular)	0.21× 0.40	0.15
$\varkappa$	0.6	0.2 - 0.7	0.3	0.55	0.5 - 2.5	0.7
shear	moderate	moderate	moderate	low	strong	strong
boundary	separatrix	separatrix	limiter	limiter	separatrix	separatrix

TABLE II. T-1 Reactor Parameters[99]

Major coil radius (m)	29.2
Minor coil radius (m)	4.0
Multipolarity	3
Coil current (MA)	36.5
Coil current density (A/cm^2)	3000
Field on axis (T)	5
Maximum field on conductor (T)	8.7
Stored energy (GJ)	460
Plasma radius (m)	2.3
Plasma volume (m^3)	3240
Average β(%)	3.54
$n\tau_E$(sec m^{-3})	$3. \times 10^{20}$
Plasma power density (MW/m^3)	1.18
Thermal power output (MW_{th})	4320
Electrical power output (MW_e)	1500

TABLE III. Heliotron Reactor Parameters[97]

Plasma β(%)	10
Average neutron wall loading (MW/m^2)	1.0
Distance from plasma to helical coil (m)	1.46
Total thermal power (MW_{th})	4961
Field on axis (T)	3.6
Plasma major radius (m)	20.9
Average plasma minor radius (m)	2.09
Plasma ion temp. (keV)	15
Ion density (m^{-3})	1.1×10^{20}

TABLE IV. Main UWTOR-M Reactor Parameters[100]

Major radius (m)	24.1
Average coil radius (m)	4.77
Coil aspect ratio	5.05
Average β(%)	5.0
Multipolarity	3
Field on axis (T)	5.5
Max. field on conductor (τ)	9.5
Coil current (MA)	35.0
No. of field periods	6
Coils for period	3
No. of coils	18
Plasma minor radius (m)	1.72
Plasma aspect ratio	14
Rotational transform at edge	1.125
Plasma volume (m^3)	1408.0
Average neutron wall loading (MW/m^2)	1.35
Thermal power output (MW_{th})	5500.0

TABLE V. MSR Reactor Design Parameters[95]

Major Radius (m)	23.24
Plasma Radius (m)	2.11
Coil current (MA/coil)	44.2
Field on axis (T)	6.0
Number of coils	18
Multipolarity	2
Number of toroidal field periods	6
Average temperature (keV)	8.0
Average density (m^{-3})	1.5×10^{20}
Average beta	0.04

TABLE VI. Reactor Design Points[94,95,100] for the Starfire Tokamak, MSR Stellarator and UWTOR-M Stellarator

	Starfire	MSR	UWTOR-M
Average beta	0.067	0.04	0.05
First-wall radius (m)	2.72	2.98	1.90
Major toroidal radius (m)	7.0	23.24	24.1
Effective geometric aspect ratio	2.57	7.8	14.
$\langle\beta\rangle B_o^2 r_p$ ($T^2 m$)	5.36	3.04	2.3
Plasma volume (m^3)	781.	2050.	1500.
Plasma chamber volume (m^3)	950.	4074.	2400.
Blanket volume (m^3)	543.	1480.	2000.
Volume enclosed by coils (m^3)	13443.	17690.	17068.
Fusion power (MWt)	3510.	4444.	4750.
Primary-coolant power (MWt)	3800.	4500.	4830.
Total thermal power (MWt)	4033.	4800.	5500.
Plasma power density (MWt/m^3)	4.50	2.34	3.17
Chamber power density (MWt/m^3)	3.70	1.18	1.98
Blanket power density (MWt/m^3)	7.00	3.04	2.38
Effective blanket power density (MWt/m^3)	7.43	3.24	2.75
System power density (MWt/m^3)	0.30	0.26	0.32
Neutron first-wall loading (MW/m^2)	3.6	1.3	1.35
Neutron energy multiplication	1.14	1.1	1.08

Figure Captions

Figure 1. Toroidal configurations: (A) tokamak. The main magnetic field is provided by poloidal coils with the poloidal field due mainly to a toroidal current in the plasma. Several external toroidal coils (which are not shown) provide a vertical magnetic field as well as drive the plasma current. (B) figure-eight stellarator. Only one set of solenoidal coils are needed. The rotational transform is generated by the torsion of the magnetic axis. (C) classical stellarator. A set of 2ℓ helical coils with current flowing in opposite directions inside the toroidal field coils provides the rotational transform. (D) torsatron. A single set of ℓ helical windings provides both the toroidal and poloidal fields. Usually an additional set of toroidal coils (which are not shown) is necessary to provide an additional vertical field. The standard heliotron configuration is similiar to this, but has an additional set of toroidal field coils.

Figure 2. The WENDELSTEIN VII-A Stellarator.

Figure 3. The HELIOTRON E device.

Figure 4. Electron energy confinement time as a function of plasma current in the CLEO Stellarator with fixed helical transform. The externally imposed transform is $\iota_H = 0.4$; $B = 1.8T$. The squares correspond to $n_e = 2\times10^{19}m^{-3}$, diamonds to $n_e \approx 1\times10^{19}m^{-3}$, and circles to $n_e = 5\times10^{18}m^{-3}$. The loss of confinement at the integral values of $q = \iota^{-1}$ is identified with instability and the formation of magnetic islands. Similar results have been obtained on many other stellarators including Model C and WENDELSTEIN VII-A.

Figure 5. Energy confinement time (lower curves) and electron temperature (upper curves) as functions of the total rotational transform at the plasma surface in the $\ell = 2$ JIPP T-2 Stellarator with B = 2.2T. Similar behavior has been observed on CLEO, L-2, WENDELSTEIN VII-A, and HELIOTRON E.

Figure 6. Operating diagram for the CLEO Stellarator with 140 kW neutral-beam injection at 20kV, with B = 1.8T, I = 100-120 kA, and $\iota = 0.35 - 0.55$. The discharge was sustained for the solid points, but not for the open circles. The externally applied rotational transform extends the operating region beyond that for a pure ohmic discharge by improving particle trapping. The crosses denote current-free operation where only a cold plasma was obtained.

Figure 7. Energy containment time in HELIOTRON E as a function of the drift velocity (or ohmic heating current) which shows improvement with decreasing current similar to that in Fig. 5. The open point was obtained in a nearly current-free plasma obtained with electron cyclotron resonance heating as described in Fig. 9.

Figure 8. Transition to current-free operation in WENDELSTEIN VII-A with neutral beam heating. The upper graph shows the programing that leads to current free operation. The lower curve describes the plasma properties. Ion temperatures were obtained from charge exchange. Electron temperatures were measured from electron cyclotron emission with the Thompson scattering points providing calibration.

Figure 9. Current-free operation of HELIOTRON E using 200 kW of electron-cyclotron-resonance heating.

Figure 10. Ion thermal conductivity as a function of plasma density, calculated with a Monte-Carlo model using the vacuum magnetic field associated with a particular torsatron winding. The solid curves correspond to predictions from an axisymmetric tokamak model and the simple helical field, or ripple transport, model. Superbanana transport is not observed.

Figure 11. Particle transport calculated with a Monte-Carlo code. Enhancement over an axisymmetric model is observed, but it is not as large as had been predicted by simple models.

Figure 12. Coils in a typical modular stellarator.

Figure 13. Intersections of magnetic field lines in the scrape-off layer with poloidal cross sections (A) beneath a coil, and (B) between the coils. The locations of the divertor regions can be determined from this type of mapping.

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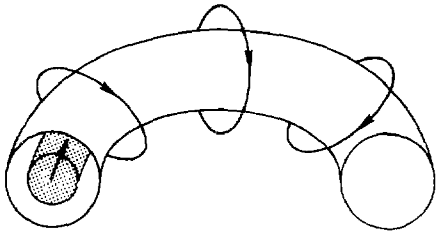
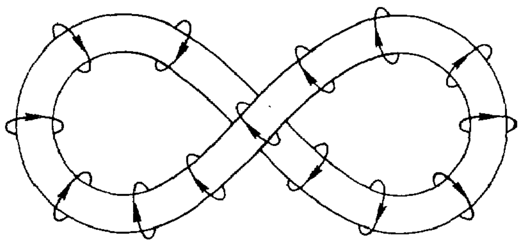


IA TOKAMAK



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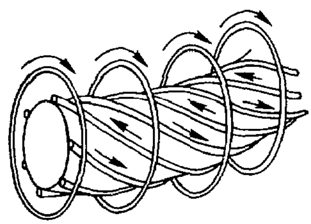

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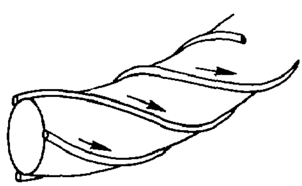


ID TORSATRON

Fig. 1

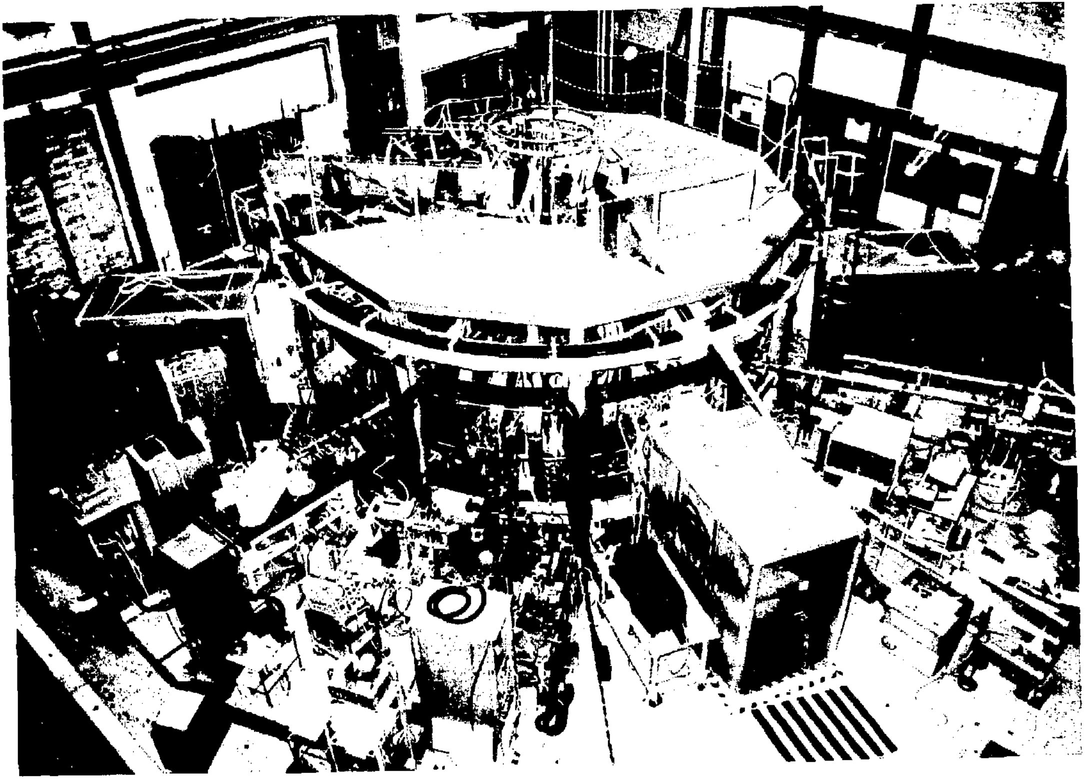


Fig. 2

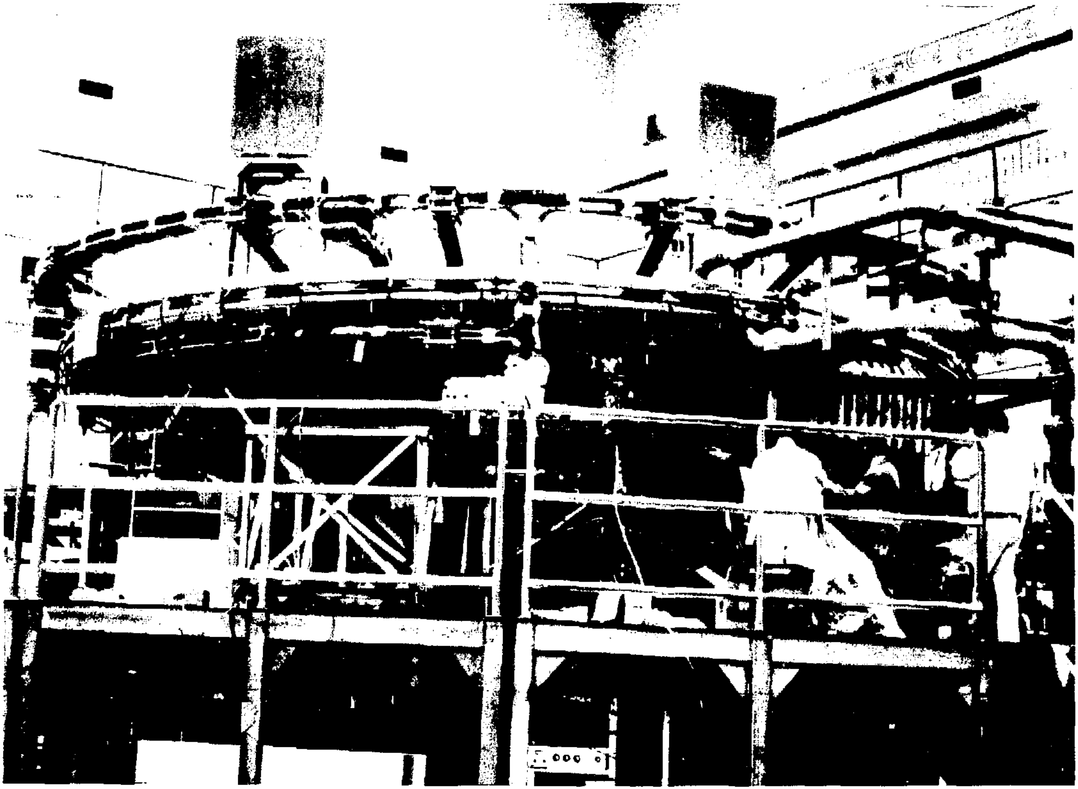


Fig. 3

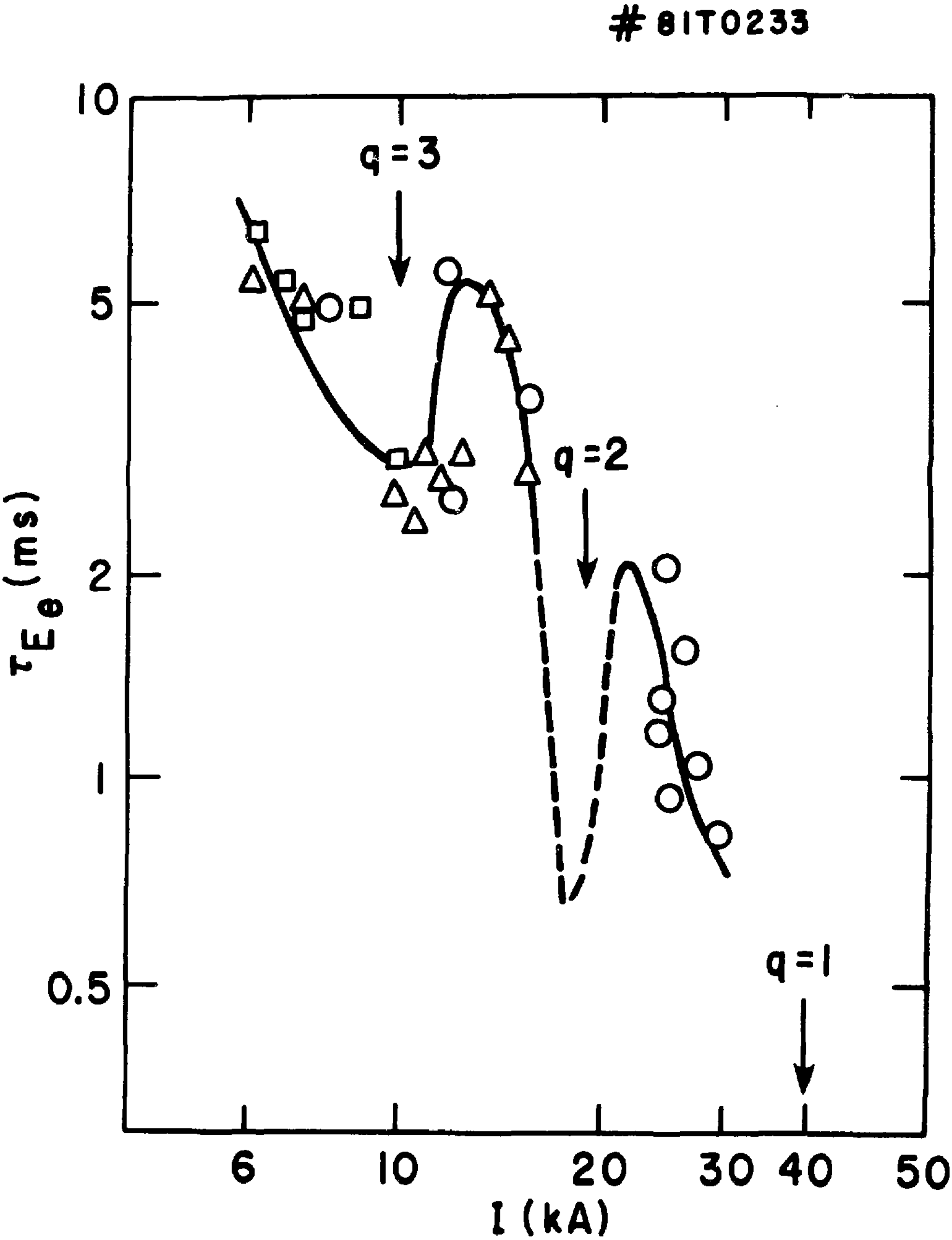
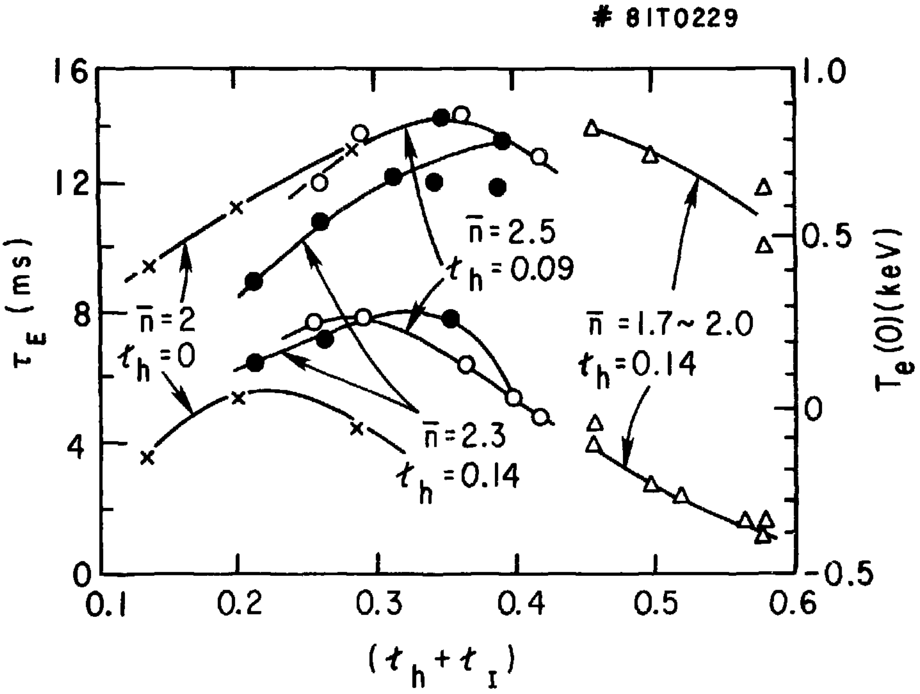


Fig. 4



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0.3
0.4
0.5
0.6
1.0
0.5
0
−0.5
τ_E (ms)
$T_e(0)$(keV)
$(t_h + t_I)$
$\bar{n} = 2.5$
$t_h = 0.09$
$\bar{n} = 2$
$t_h = 0$
$\bar{n} = 2.3$
$t_h = 0.14$
$\bar{n} = 1.7 \sim 2.0$
$t_h = 0.14$

Fig. 5

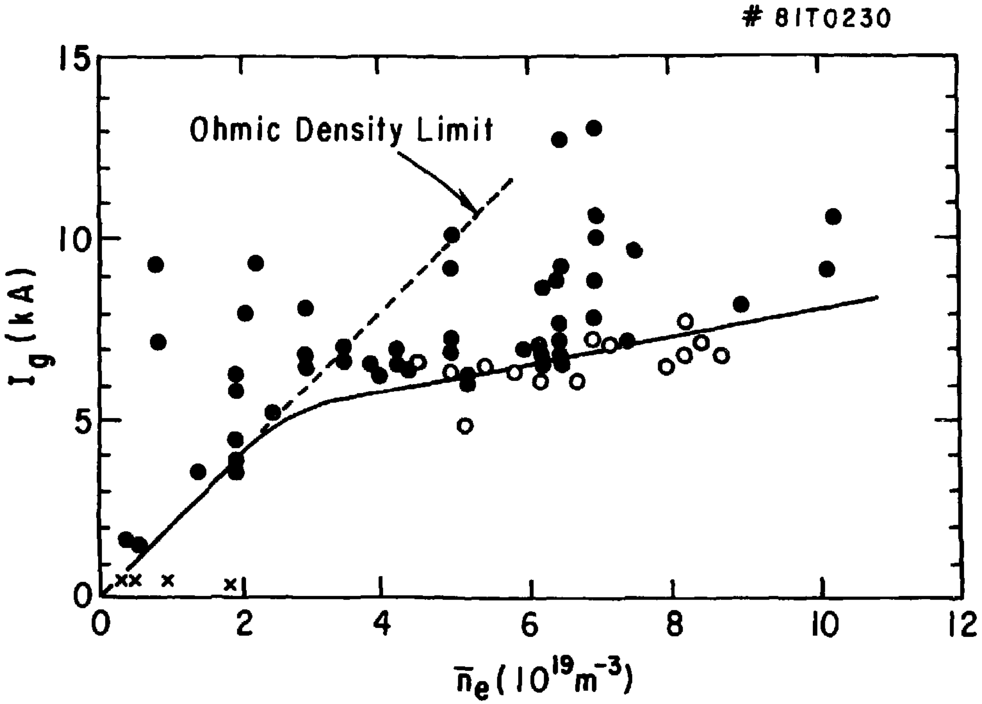

81T0230
Ohmic Density Limit
I_g (kA)
$\bar{n}_e$ (10^{19} m^{-3})
0
5
10
15
0
2
4
6
8
10
12

Fig. 6

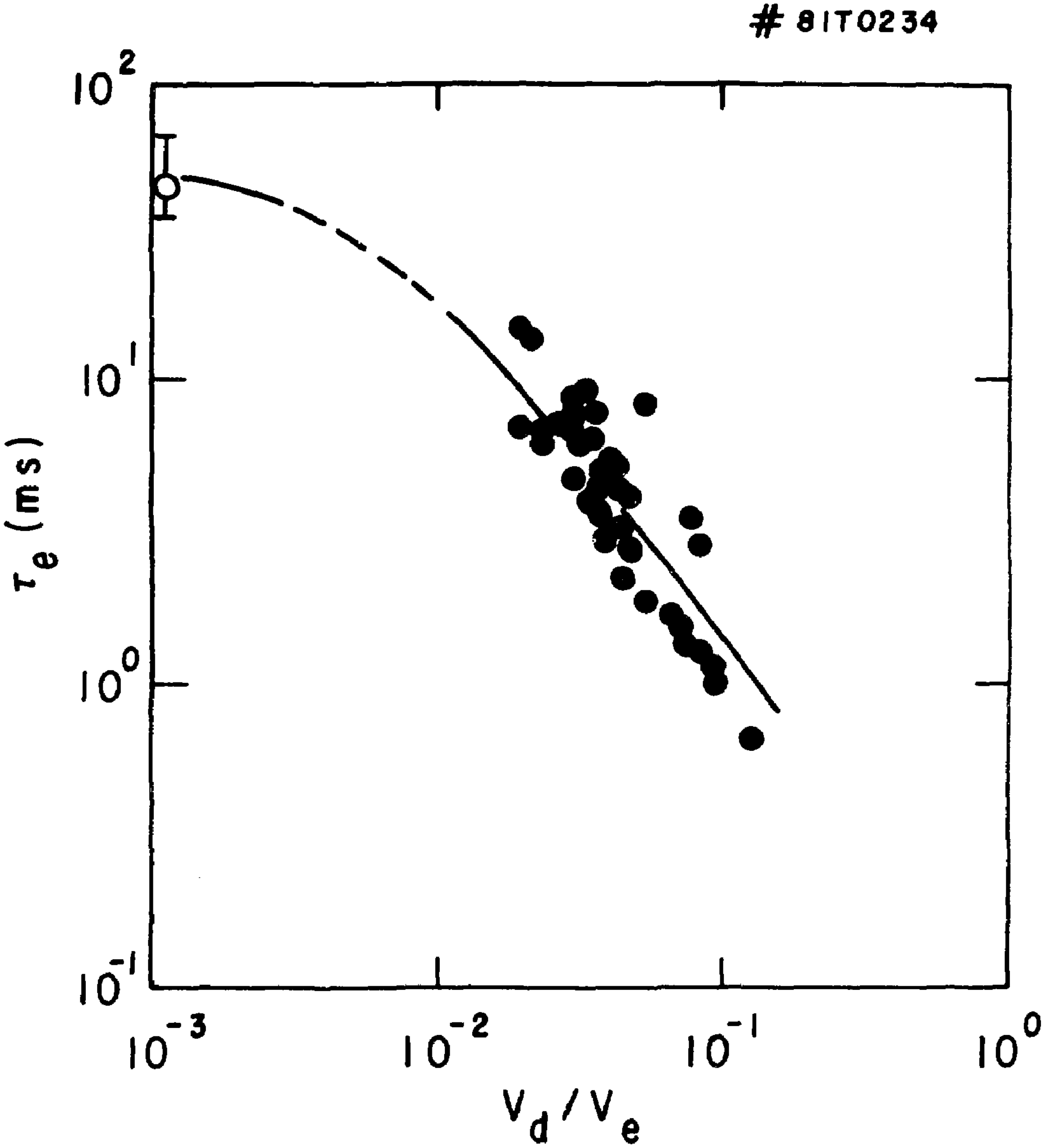
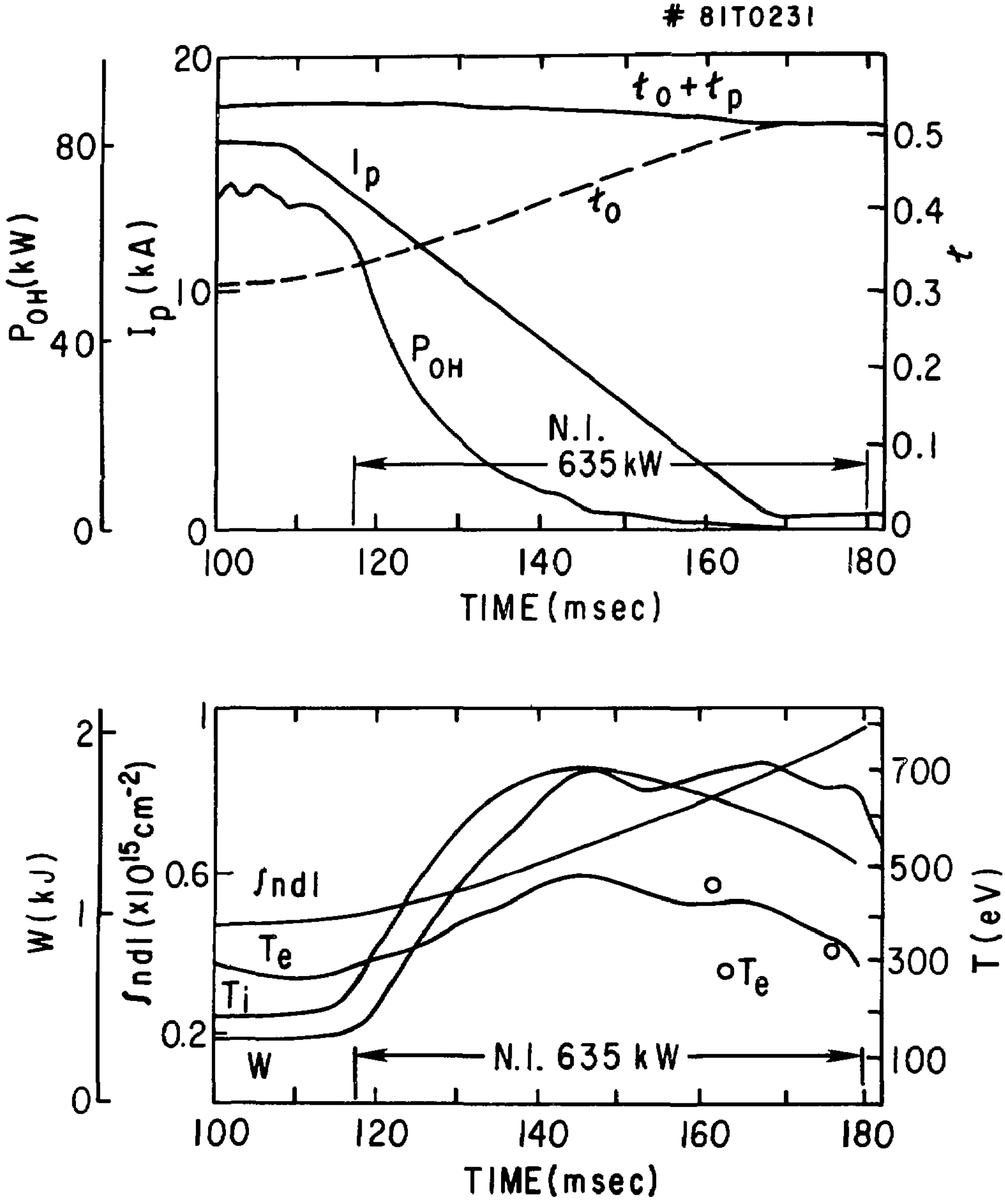
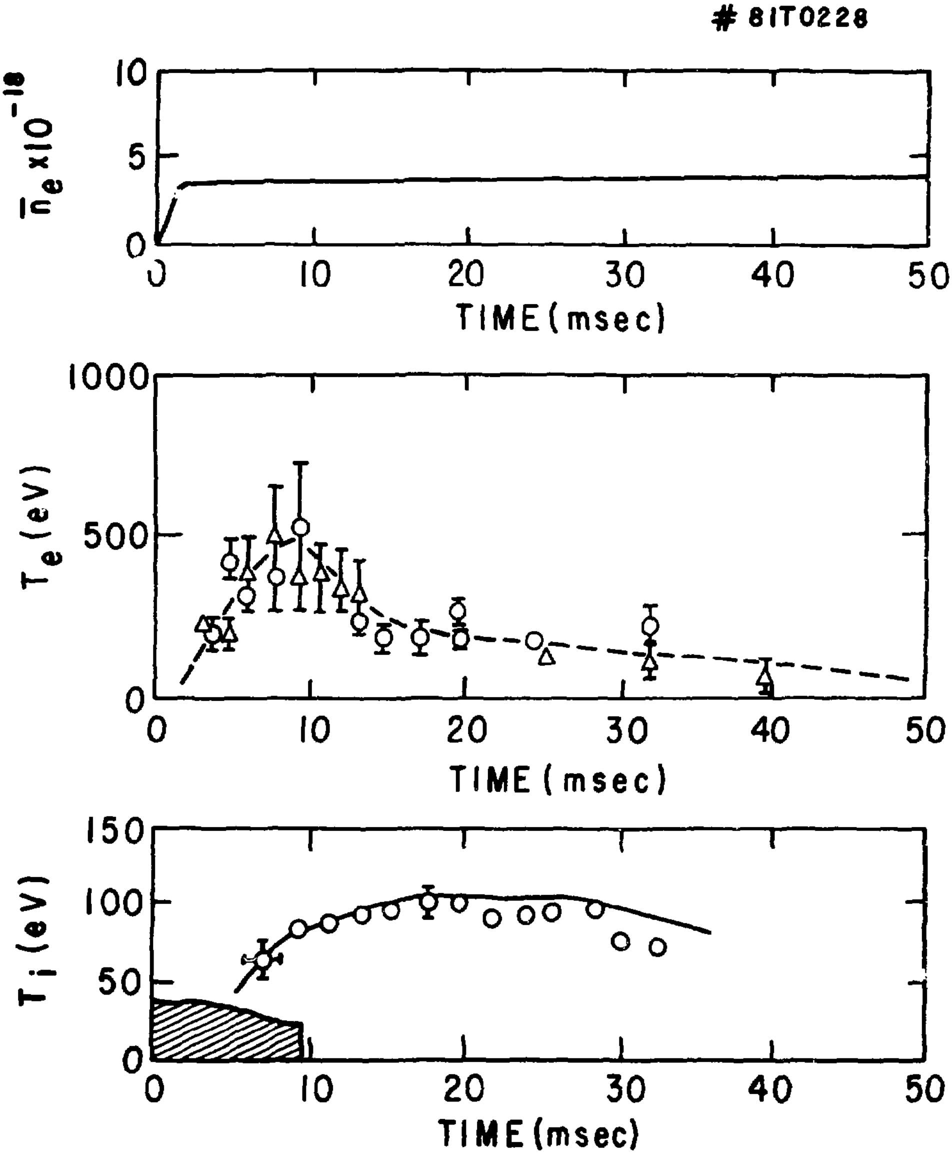


Fig. 7



81T0231
t_0+t_p
I_p
t_0
P_{OH}
N.I. 635 kW
P_{OH}(kW)
I_p(kA)
TIME(msec)
∫ndl
T_e
T_i
W
oT_e
N.I. 635 kW
W(kJ)
∫ndl (x10^{15}cm^{-2})
T(eV)
TIME(msec)

Fig. 8



81T0228
$\bar{n}_e \times 10^{-18}$
10
5
0
0
10
20
30
40
50
TIME(msec)
T_e (eV)
1000
500
0
0
10
20
30
40
50
TIME(msec)
T_i (eV)
150
100
50
0
0
10
20
30
40
50
TIME(msec)

Fig. 9

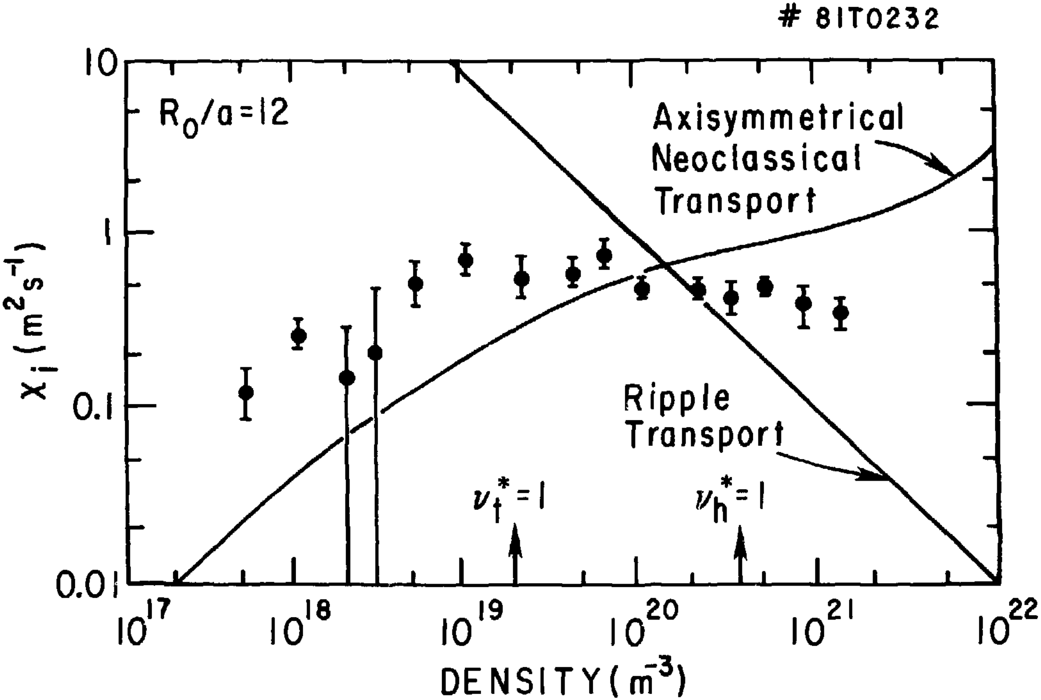

81T0232
10
1
0.1
0.01
χ_i ($m^2 s^{-1}$)
$R_0/a=12$
Axisymmetrical
Neoclassical
Transport
Ripple
Transport
$\nu_t^*=1$
$\nu_h^*=1$
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
DENSITY (m^{-3})

Fig. 10

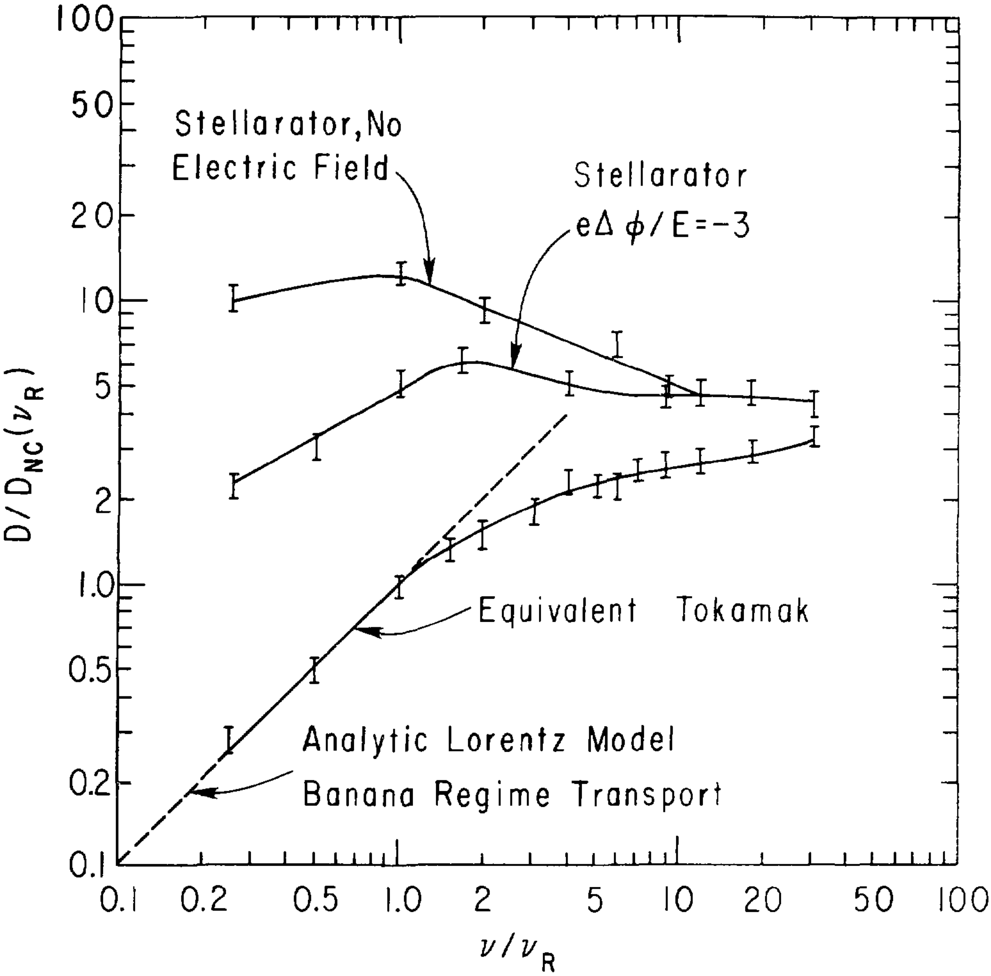

Stellarator, No
Electric Field
Stellarator
eΔ φ/E=-3
Equivalent Tokamak
Analytic Lorentz Model
Banana Regime Transport
D/D_NC(ν_R)
ν/ν_R
100
50
20
10
5
2
1.0
0.5
0.2
0.1
0.1 0.2 0.5 1.0 2 5 10 20 50 100

Fig. 11

#81T0235

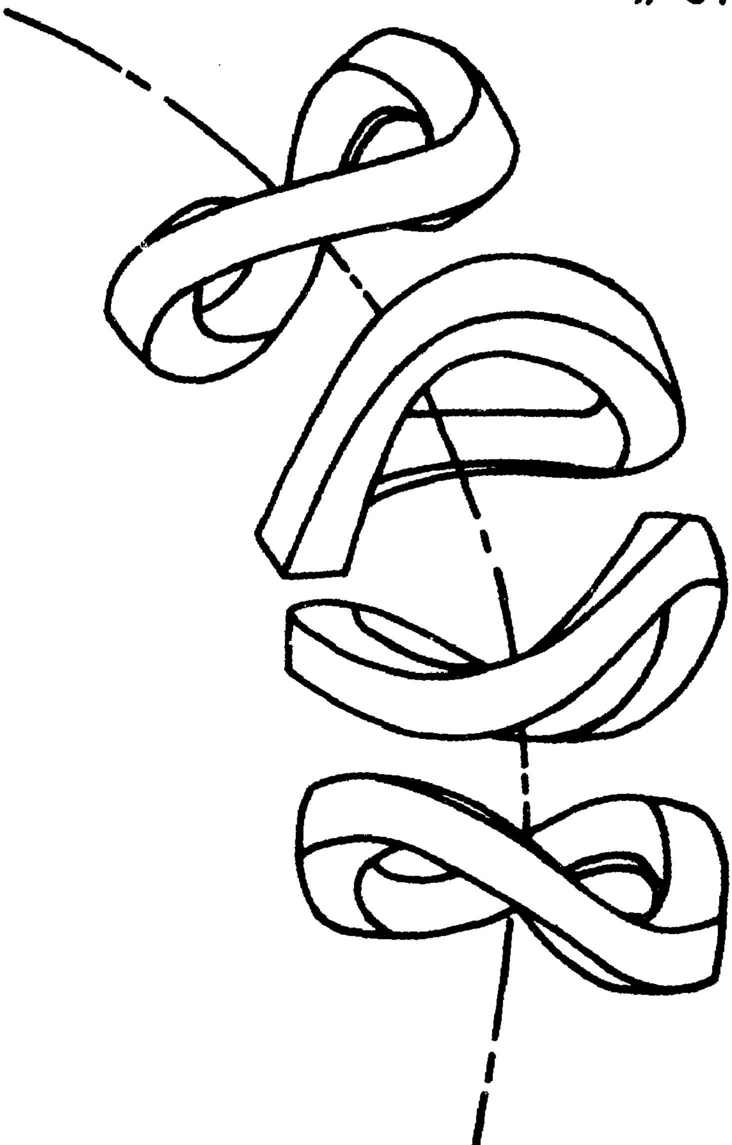


Fig. 12

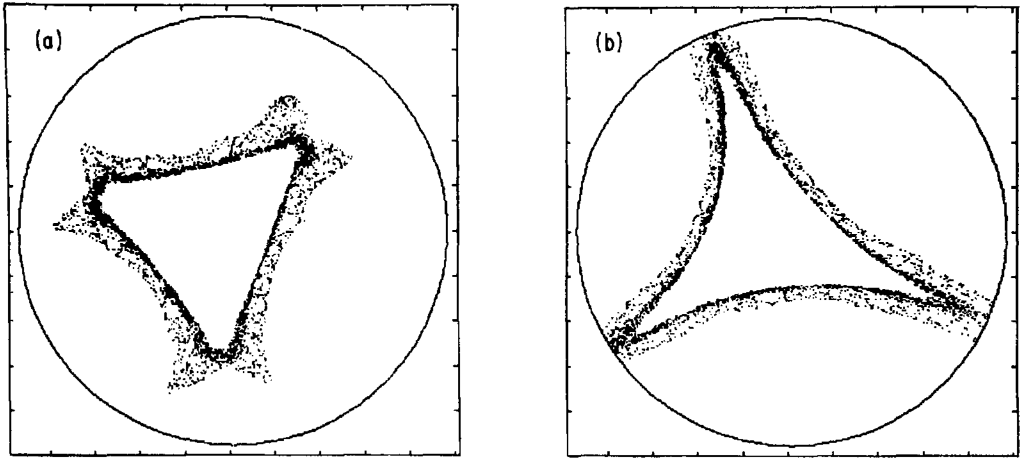


Fig. 13