STELLARATORS
Present Status and Future Planning

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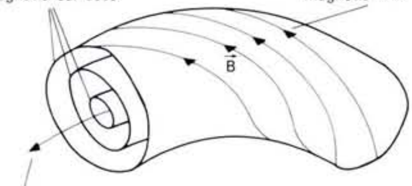

Fig. 1 — Period of toroidally closed magnetic surfaces.

The stellarator is a closed toroidal device designed to confine a hot plasma in a magnetic field. It is one of the oldest concepts to have been investigated in the search for controlled thermonuclear fusion.

The basic idea of the stellarator was developed by Lyman Spitzer, Professor of Astronomy at Princeton in 1951[1]). Experimental studies began in 1952 and after the declassification of fusion research in 1958 the idea was picked up by other research groups. In Europe, the first stellarators were built in the Max-Planck Institute for Physics and Astrophysics in Munich and later at Culham, Moscow and Karkhov. Stellarator experiments have also been constructed at Nagoya and Kyoto in Japan. It was following the conversion in 1969 of the Princeton model-C stellarator into another toroidal type, the tokamak, that interest in stellarators began to decline world-wide. The main reason for the change was the large plasma loss which was found in the C-stellarator, and which was termed anomalous because it could not be explained on the basis of inter-particle collisions.

It was believed moreover, that the loss could be expressed as a Bohm diffusion coefficient D which was proportional to T_e/B, the ratio of the electron temperature to the mean magnetic field. If this was indeed true, then it was not possible to establish a self-sustained thermonuclear reaction in a stellarator reactor. During the past 10 years however, results obtained on other stellarators, notably the WENDELSTEIN VII-A stellarators in Garching have changed the picture completely. Stimulated by the information coming out of the two largest stellarators WENDELSTEIN VII-A in Garching[2]) and HELIOTRON E in Kyoto [3]) there is now an increasing interest in the system which has led to new ideas and new concepts for improving stellarator configurations and constructing new experiments.

Basic Principles of the Stellarator

For a plasma to be confined magnetically, fields are created which allow the plasma to expand freely along the field lines and these form continuous magnetic surfaces. In ideal circumstances, the plasma then develops an isotropic Maxwellian energy distribution. Losses occur only in directions perpendicular to the surfaces via Coulomb collisions and collective phenomena like instabilities and turbulence. In open-ended configurations like mirror machines (see *EN,* **12** 8/9) there are always plasma particles which escape the confinement volume along the magnetic field and an isotropic distribution function cannot be maintained. If this anisotropy is too strong it gives rise to instabilities and enhanced plasma losses. It is mainly to avoid these disadvantages that toroidal confinement has been preferred.

In toroidal configurations, the currents which generate the confining magnetic fields can be classified under three categories:

- external currents which generate a vacuum field ($\vec{B}$);
- currents in the plasma largely perpendicular to the vacuum field which via the Lorentz force balance the gas pressure under equilibrium conditions: $\nabla p = \vec{j} \times \vec{B}$;
- toroidal currents, flowing mainly parallel to the magnetic field.

In a tokamak, the toroidal current is necessary for the confinement as well as providing ohmic heating. However the current has to be generated by induction from outside the plasma and no steady state operation is possible.

In contrast to the tokamak, the stellarator concept is aiming at plasma equilibrium with no net toroidal current, in which case, steady state operation is possible, a great advantage from the view-point of a future fusion reactor. Unfortunately, plasma equilibria with no net toroidal current cannot be axisymmetric, and conditions are not uniform around the torus but instead consist of three-dimensional configurations without symmetry. This fact has made theoretical investigation of stellarator systems difficult in the past, although in recent years considerable progress has been made through the use of powerful computers.

The general stellarator equilibrium is characterized by the following properties: A set of nested toroidal magnetic surfaces surrounds one closed field line, the magnetic axis (Fig. 1). The magnetic field lines on each surface are either closed or cover the whole surface ergodically. Plasma pressure is maximum on the magnetic axis and zero on the last magnetic surface.

The analysis of closed magnetic surfaces in magnetic fields is a complicated mathematical problem, as only in special circumstances do the lines of force form a magnetic surface and, in practice, the topology of magnetic surfaces is investigated by field line integration. The topology of the field lines is determined by the rotational transform or twist number $\iota/2\pi$ (or $\iota\!\!-$), which is the number of revolutions of a field line around the magnetic axis during one toroidal revolution.

The need for a helical field can be understood from a look at the particle orbits. Charged particles tend to follow the field lines and unless these are helical, because of inhomogeneities, the particles will drift away to the plasma boundary and be lost. The helical field however, ensures that they rotate about the magnetic axis which results in their drift motion averaging out. The particle orbits stay in the vicinity of the magnetic surface with a deviation of only a few gyro radii. Thus the stellarator field is an ideal trap for "passing" particles, i.e. those with sufficiently large velocity parallel to the magnetic lines of forces ($v_\parallel >> v_\perp$). In the opposite case $v_\parallel << v_\perp$, particles can be trapped between two maxima of $|B|$ along the lines of force, as in a mirror. These localized particles do not see the averaging effect of the rotational transform and have a tendency to drift out of the confinement region. Localized particles distinguish the stellarator from the axisymmetric tokamak where all particle orbits are bounded — if their energy is not too large.

In addition to the drift of these localized particles, the minimum loss in a fusion plasma is determined by Coulomb collisions and if the total is too large, ignition of a fusion plasma is not possible. The Coulomb collision-dominated loss processes in toroidal configurations are described by neoclassical theory and in recent years a better understanding of the stellerator situation has been obtained by means of Monte-Carlo calculations. Also ways have been found of reducing the drift of passing and localized particles by proper shaping of the magnetic field configuration.

In the stellarator, the main contribution to the magnetic field is produced by external coils. The magnetic fields produced by the plasma currents are merely of the order of β, (the ratio of the plasma pressure to the magnetic pressure $= 8\pi p/B^2$) which has generally a low value. The self-generated fields $\vec{B}_1$ have nevertheless important consequences for plasma equilibrium as they lead to a distortion and shift of the magnetic surfaces of the vacuum field $\vec{B}_0$,

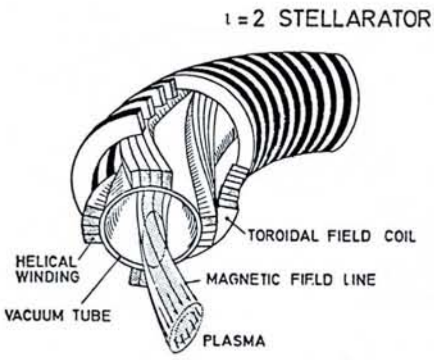

Fig. 2 — Schematic picture of a section of an ι = 2 stellarator with two pairs of helical windings. The elliptical cross-section of the magnetic surfaces rotates with the windings.

setting an upper limit on the plasma pressure for a given B. In stellarator experiments so far, this limit has not played a serious role, but with β-values of 5% or more envisaged, the choice of the vacuum field will become more restricted. On the other hand, in Garching, specific configurations have been found theoretically which show small toroidal shifts of the magnetic axis (Shafranov shift) and thereby allow larger β-values[5]).

Another serious problem is the magnetohydrodynamic stability of the plasma. A vacuum field which provides stable confinement of a low-β plasma can easily be found, but with increasing plasma pressure, the free energy stored in the pressure and also in the plasma currents increases, and beyond a certain threshold of β this free energy is available for MHD instabilities. The precise value of the threshold, critically depends on the properties of the vacuum magnetic field and has been the subject of a major effort of theoretical investigation over many years. Although the studies are by no means complete, it is now commonly believed that stable stellarator equilibria with an averaged β-value of 5 — 10% do exist.

Stellarator Experiments

In stellarator experiments, the choice of the magnetic field configuration and the choice of the heating method are of particular importance. As the external coil system has to generate toroidally closed flux tubes with helical lines of force, the coil system itself has to incorporate the helical geometry. The first idea — already proposed by L. Spitzer — was to modify the coil set of a solenoid so that the centre line of the coils was no longer a circle but a closed line helically wound around a circle. Soon, an easier method was found: while the circular coils of a solenoid generate the major part of the magnetic field $\vec{B}_0$, a set of helical windings provides the necessary poloidal field and determines the geometry of the flux tubes and the value of the rotational transform. In most experiments these helical windings are wound on the vacuum tube and are in pairs, alternate windings carrying currents in opposite directions. According to the number of helical windings carrying current in a given direction one distinguishes between ι = 1, 2, 3 — stellerators.

Whilst most stellarators have been built according to this principle, it is also possible to generate toroidal magnetic surfaces with a finite rotational transform, with windings carrying parallel currents. In this special case, the device is called a torsatron.

The Princeton model-C stellarator had the shape of a racetrack with straight sections and curved sections and carried helical windings in the curved sections only. This method provides easy access to the straight sections, but because of the large deviation from axisymmetry there exists the danger of destroying the magnetic surfaces by small error fields. Other experiments like the WENDELSTEIN stellarators in Garching, CLEO in Culham and the stellarators in Moscow are designed to approach as closely as possible an axisymmetric configuration. Recently the idea of a stellarator with straight sections has been taken up again by B. Kadomtsev and others in the Kurchatov Institute, Moscow[6]).

For experimentation, the concept of helical windings and separate main field coils provides a convenient method of varying the magnetic field configuration. At reactor dimensions, however, these helical windings would impose severe technical problems. As a result, alternative solutions have been worked out based on a set of specially shaped closed poloidal coils (Fig. 3).

The idea of twisted coils, proposed by S. Rehker and H. Wobig in 1972[7]) has since been adapted and improved by other authors[8]). Studies of stellarator reactors are based on this concept and employ a modular set-up for the coil system[9]). Present-day stellarator experiments still use helical windings but for future experiments, modular coil systems are already being planned.

Plasma Heating

Many of the heating methods used in stellarator experiments are not specific to the system but are also applicable to tokamaks: ohmic heating by an induced toroidal current, injection of high energy neutral particles and high frequency heating in the ion cyclotron and electron cyclotron frequency range (*EN,* **9** 1/2). Other methods like plasma injection by a plasma gun, ionization of a hydrogen pellet by laser irradiation or the build-up of an alkali plasma by contact ionization can only be applied to stellarator experiments which have no ohmic heating. Moreover as they can produce only low density and low temperature plasmas, most attention has been paid to experiments where ohmic heating is incorporated. With such devices, plasma parameters comparable to those obtained with tokamaks can be obtained: density $n = 10^{19}$ - 10^{20} m^{-3}, temperature $T_e \leq 1$ keV. Examples of stellarators with ohmic heating are WENDELSTEIN VII-A (Garching), HELIOTRON E (Kyoto), URAGAN (Karkhov) and L-2 (Moscow). The CLEO stellarator (Culham) is no longer in operation.

In Table 1 a list of major stellarator experiments is given.

Stellarators with ohmic heating exhibit the following characteristics:

1. Electron confinement is similar to that found in tokamaks with comparable parameters. In addition the thermal conductivity of the electrons is anomalously large and follows a law of the type:

$$\chi_e \sim 1/n\, T_e^{\alpha}$$

where $\alpha < 1$, n = density

2. Energy confinement of ions is close to the predictions of neo-classical theory (based on Coulomb collisions).

3. Instabilities driven by the ohmic heating current which are so disruptive in tokamaks are stabilized by the helical field.

Table I — Parameters of Stellarator Experiments

	Major Radius, m	**Plasma Radius,** cm	**Magnetic field,** T
HELIOTRON E (Kyoto, ι = 2 torsatron)	3.2	22	2
WENDELSTEIN VII-A (Garching, ι = 2 stellarator)	2	11	3.5
CLEO (Culham, ι = 3 stellarator)	0.9	13.5	2
URAGAN II (Karkhov)	racetrack	10	2
URAGAN III (ι = 3 torsatron)	1	17	3—4
L—2 (Moscow, ι = 2 stellarator)	1	11	2
WENDELSTEIN VII-AS (Garching, planned)	2	20	3

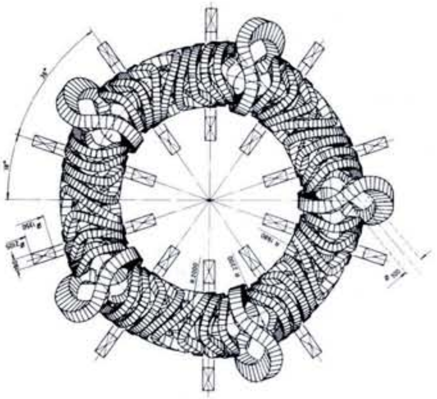

Fig. 3 — Top view of the coil set of the proposed stellarator WENDELSTEIN VII-AS. The five large coils are designed to give access to the interior for neutral beam injection. The diameter of the coils is about 1 m.

The importance of the first two results is that they contradict the early views on Bohm diffusion scaling in stellarators. The third result is of more interest for tokamak research as it may contribute to a better understanding of current driven instabilities.

Ohmic heating however, as already explained, implies pulsed operation whereas the goal is a reactor operating continuously. The essential aim therefore of stellarator experiments today is the maintenance of a plasma without ohmic heating currents. Major progress has been achieved by the neutral beam heating experiments in WENDELSTEIN VII-A and by electron cyclotron heating experiments in HELIOTRON E. In WENDELSTEIN VII-A an ohmically heated plasma is used as the target plasma for neutral beam injection. During the injection phase, the toroidal current decays and the currentless plasma is maintained by neutral beam heating only. With a plasma density of 10^{20} m^{-3} and a temperature of 300-600 eV the β-value is close to 1%. Plasma losses are clearly reduced in this currentless phase compared to the ohmically heated phase but the quantitative scaling laws have not yet been evaluated. Another important problem is the origin and transport mechanism of impurity ions during the currentless phase as, at the end of the injection phase, radiation from these dominates the power balance.

The neutral beam heating experiment in WENDELSTEIN VII-A has clearly demonstrated that a currentless high density plasma can be maintained by a moderate heating power, the net input being only about 200 kW. The maximum β-value of 1% achieved is encouraging but it is still too small to test the stability limits described earlier.

In HELIOTRON E, a currentless plasma with a density of $n \leq 10^{19}$ m^{-3} and a temperature of $T_e = 500$ eV could be obtained by electron cyclotron heating. The analysis of this experiment suggests that even electron energy transport might be close to the predictions of neo-classical theory. Further stellarator experiments are needed to confirm this important property. Neutral beam injection in HELIOTRON E has heated the plasma to 600 eV at a density of $n = 3.10^{19}$ m^{-3}, but in this case, an ohmic heating current was still present. Currentless operation is planned as a next step. These two examples do not give a complete survey of present stellarator experiments but they indicate the essential results and the open questions to be tackled in the future.

Future Planning

The main objectives of the next experiments are to:

- investigate the nature of the transport mechanism in currentless operation;
- test the limits of β for equilibrium and stability;
- clarify the role of impurity atoms;
- improve the heating methods and extend the plasma parameters to higher temperatures.

To this end new experiments are being planned in several laboratories.

After the experimental success of WENDELSTEIN VII-A and HELIOTRON E, interest in stellarators has grown again in the major fusion laboratories. Several new concepts are under study and proposals for new devices are submitted for approval. In the USA two groups at the University of Wisconsin and at the Oak Ridge Laboratory are studying the torsatron concept with the aim of building an experiment comparable in dimensions with present-day tokamaks. The idea is to make use of a modular coil system instead of the conventional helical windings.

Also at the University of Princeton a new and interesting concept called HELIAC has been developed. The magnetic axis of this configuration is no longer circular as in classical stellarators but encircles a toroidal conductor which produces a poloidal field. The main toroidal magnetic field again is generated by circular coils which are adjusted to the helical shape of the magnetic surfaces. In some sense this configuration is the reversal of a classical stellarator: instead of the current carrying windings being helical, it is the plasma column and the external coil system consists of circular coils (Fig. 4). Still unsolved is the question of modularity of this coil system since the coils are interlinked. Theoretical studies of the HELIAC configuration indicate a high equilibrium and stability limit of β.

As already mentioned, in Garching theoretical optimization of stellarator equilibria has been going on for some years[5] with the aim, as defined by A. Schlüter, of finding stellarator equilibria with reduced plasma currents. The plasma currents $j_\perp$ and especially $j_\parallel$ are responsible for the Shafranov shift and the equilibrium limit, so that a reduction of $j_\parallel$ should increase the equilibrium β-limit. Simultaneously the collisional diffusion losses (neo-classical Pfirsch-Schülter diffusion losses) are reduced in configurations with small $j_\parallel$. Methods of calculating vacuum magnetic fields with the postulated properties have

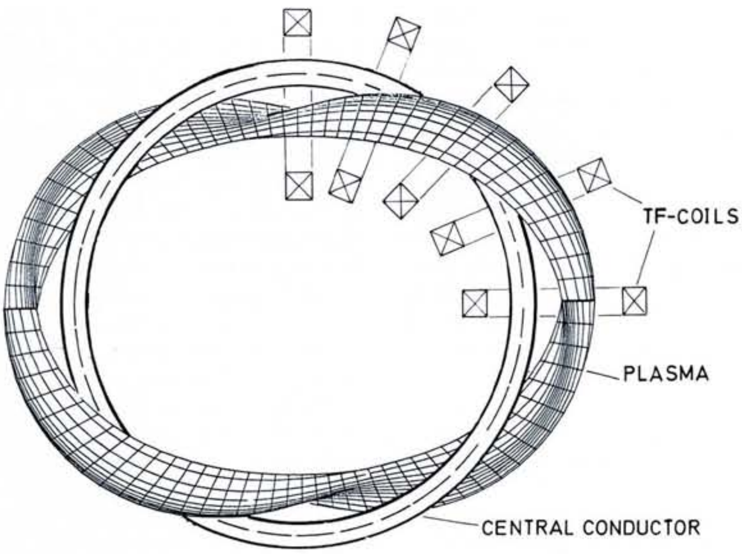

Fig. 4 — Schematic of the HELIAC configuration. Only one quarter of the TF-coil set is shown.

also been worked out as well as the design of coils to generate these fields. This "Advanced Stellarator" concept has resulted now in a proposal to modify WENDELSTEIN VII-A — called W VII-AS — which has been submitted to Euratom and is in its decision phase.

The aim of the experiment is to test the effects predicted by the optimization of the magnetic field. Owing to the smaller deviation of particle orbits from magnetic surfaces, the classical collisional losses in W VII-AS are expected to be a factor of two smaller than those in a conventional $\iota = 2$ stellarator. As the extension of the plasma parameters to the long mean free path regime and to its β-limits requires powerful heating methods, in W VII-AS, several heating methods with more than 1 MW power are planned: neutral beam injection, ion cyclotron heating and electron cyclotron heating. A major aim is the build-up of a plasma without ohmic heating currents from the very beginning of the discharge. It is expected that this procedure will also simplify the investigation of impurity transport processes. A new and ambitious feature of the W VII-AS proposal is the modular coil set consisting of poloidally closed and twisted coils (see Fig. 3).

The optimum adjustment of coils to the shape of the magnetic surfaces and the maximum magnetic field of 3T requires that all coils be different. The coil-set is thus highly complex and leads to asymmetric forces and stresses. Detailed stress analysis, however, has shown that the mechanical problems are within the present technical limits. The estimated construction time of W VII-AS is three years.

Reactor studies on the basis of a modular coil-set have already started in Los Alamos, Madison and to a certain extent also in Garching. These studies are useful in order to investigate detailed technical problems such as the mechanics of the coil system. Nevertheless it is still far too early to construct a self-consistent reactor model, and further theoretical and experimental studies are needed on the optimum magnetic field configuration, its β-limits and its loss mechanisms, the steady state conditions and the behaviour of impurities, before a conclusive statement about the physical and technical feasibility of a stellarator reactor can be made. Nevertheless, the long-term goal of a steady state system justifies the effort.

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