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Plasma Confinement in Stellarator Systems

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Plasma confinement in stellarator systems

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The stellarator is a plasma confinement system in which the magnetic field configuration is produced by currents in conductors outside the plasma. Plasma current is not necessarily required for confinement or for heating the plasma.

Results from the CLEO and W VIIA experiments are presented to illustrate the progress in the understanding of containment and heating in the stellarator configuration.

1. Introduction

The stellarator concept originated in Princeton University under the direction of Professor Lyman Spitzer Jr (1958) during the early 1950s. It has been further developed in the Soviet Union, Japan, Garching and Culham. Basically the configuration represents a novel solution to the problem of toroidal plasma confinement. The necessary twist of the field lines to provide equilibrium is produced by a combination of a toroidal solenoidal magnetic field and the field due to a number, $2l$, of multipole helical conductors wound on the outside of the toroidal vacuum chamber as in figure 1. Unless the field is degenerate, field lines close on themselves only after an infinite number of passes around the machine. In doing so they lie on the nested magnetic surfaces whose extent depends on the form and strength of the helical field. If this field is weak the plasma confinement region has to be determined by a material limiter, as for a tokamak. If the field is strong there is a natural magnetic separatrix inside the containing vessel. The angle of twist of the field line is called the 'rotational transform' ι and is related to the tokamak safety factor as $\iota = q^{-1}$.

2. Objectives of stellarator research

Since the fields are formed by currents in external conductors the configuration represents a possible steady-state reactor system with consequent technological and engineering advantages. It is therefore studied as a basic toroidal confinement system with a view to assessing its reactor potential. In particular, it is important to investigate whether the external rotational transform is effective in providing an equilibrium condition for confining plasma. By comparison with the earlier Princeton experiments, the poloidal field produced by the external conductors has been greatly increased by increasing the minor radius of the plasma with respect to the major radius (aspect ratio). For some time other experimental work on the configuration was limited to small machines with low temperature plasma, but the parameters now obtainable are comparable with those in tokamaks.

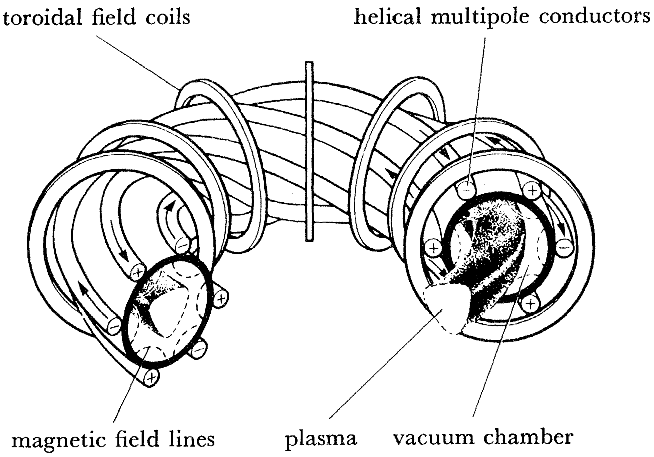

FIGURE 1. The stellarator configuration.

TABLE 1. PARAMETERS OF CLEO AND W VIIA

	W VIIA	CLEO
helical winding, l/m	$\frac{2}{5}$	$\frac{3}{7}$
mean major radius/m	2.0	0.9
toroidal field, B_{ϕ}/T	3.5	2.0
duration of fields/ms	2500	500
plasma radius/m	0.11	0.1
limiter radius/m	0.13	0.13
ohmic heating current/kA	$\leqslant 40$	$\leqslant 40$
mean electron density/m^{-3}	$\leqslant 10^{20}$	$\leqslant 10^{20}$
electron temperature/eV	$\leqslant 1000$	$\leqslant 800$
ion temperature/eV	$\leqslant 400$	$\leqslant 300$
energy replacement time/ms	$\leqslant 16$	$\leqslant 12$

Although plasma current, as used in tokamaks, is not necessary for heating stellarator plasmas most of the current series of stellarator experiments make use of this method of producing and heating plasmas. This has enabled comparisons to be made between stellarator and tokamak confinement in the same apparatus. This paper discusses the properties of ohmic heated plasmas in the light of results from the Wendelstein W VII A experiments (W VII A team 1977*a*, *b*, 1979*a*, *b*) (Garching) and the CLEO experiment (Culham) (Atkinson *et al.* 1976, 1977*a*, *b*, 1979*a*, *b*). Since one of the important advantages of the configuration is its ability to contain plasma in the absence of current, experiments have also been conducted on the auxiliary heating of plasmas with little or no current. Results from these are also discussed, again using as examples the work of the W VII A and CLEO groups.

The main parameters of the two machines are shown in table 1.

3. OHMIC HEATED PLASMAS

Figure 2*a* shows the effect of a plasma current on the external rotational transform produced by the helical winding, for the CLEO stellarator. The general effect is to reduce the shear and to make the configuration susceptible to effects occurring at rational magnetic surfaces, where the field lines close on themselves after a small number of transits, i.e. where $\iota = \frac{1}{3}$ or $\frac{1}{2}$. That this has a real effect on containment can be seen from figure 3 in which the electron energy replacement time τ_{Ee} is plotted against plasma current. This quantity is defined as the ratio of the electron energy content of the plasma to the ohmic power input.

One significant effect which has been observed in CLEO is the saturation of τ_{E} as the plasma density is increased (figure 4). At the lowest density, thermal losses are determined by electron conduction, and τ_{E} increases with increasing density, while at higher density the

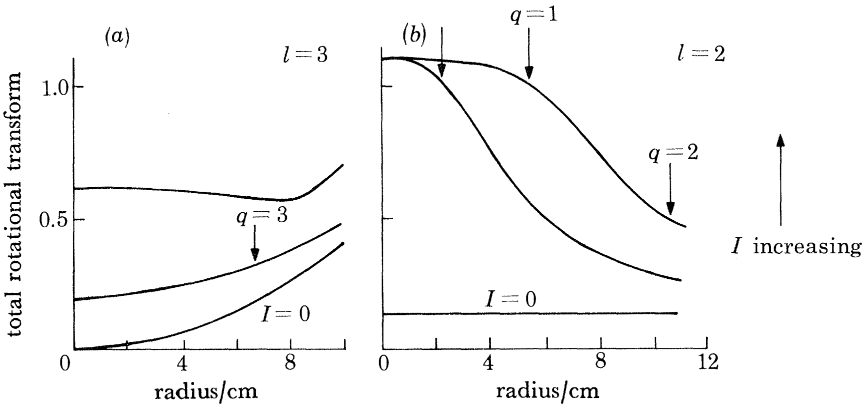

FIGURE 2. Total rotational transform against radius at different values of plasma current for (*a*) CLEO, (*b*) Wendelstein VII A.

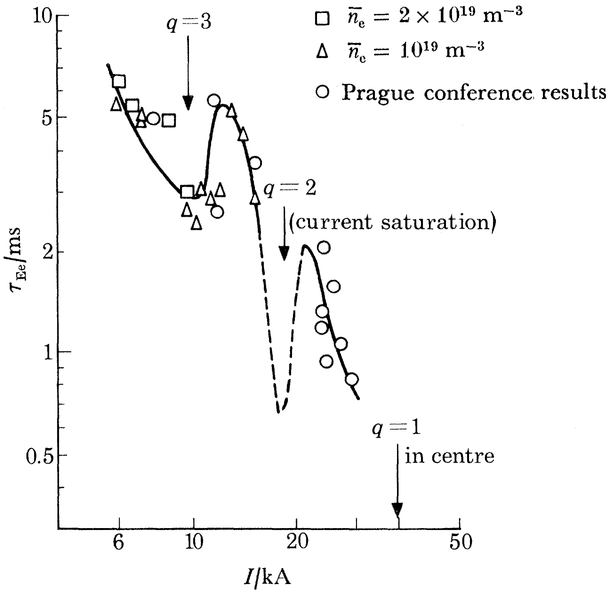

FIGURE 3. Electron energy replacement time against plasma current for CLEO, showing the effect of rational magnetic surfaces; $B_\phi = 1.8$ T, $t_0 = 0.4$.

thermal losses are dominated by ion thermal conduction. A detailed energy balance shows that, in contrast to a tokamak, the external transform assists ion heating and confinement, and so the increased ion thermal conductivity can easily dominate the electron losses.

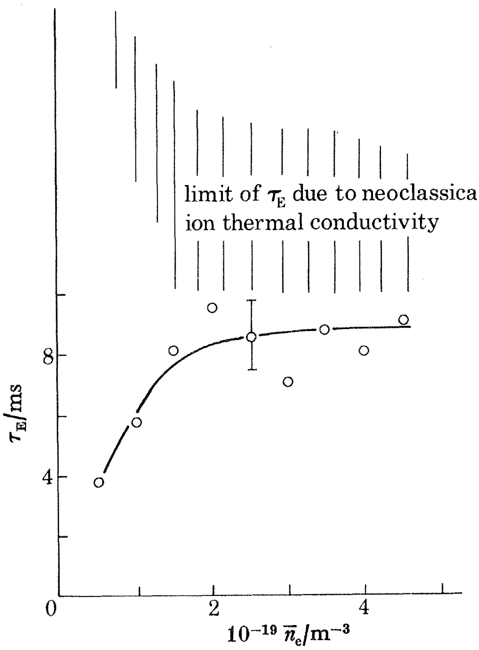

FIGURE 4. Energy containment time against mean plasma density for CLEO; $B_\phi = 1.86$ T, $I = 6$ kA.

The W VII A stellarator shows contrasting results. The variation of rotational transform with radius is shown in figure 2*b*, in which it can be seen that this behaviour is similar to that in a tokamak and that the thermal losses may be expected to be tokamak-like, i.e. for electron losses to be the dominant feature. Figure 5 shows the scaling of electron temperature diffusivity χ_e with electron temperature, which gives the following law:

$$\chi_e \propto \frac{I}{B_\phi} \frac{1}{nT_e^{0.66}},$$

a result which is very similar to the scaling laws discovered for some tokamaks (Coppi & Mazzucato 1979). In conditions where electron losses dominate in CLEO, similar scaling laws can be found. The significant achievement of W VII A lies in the fact that the value of χ_e is a locally measured quantity rather than a global energy replacement time.

4. CURRENTLESS PLASMAS AND AUXILIARY HEATING

Because of the steady-state reactor properties of the system, it is important to investigate the confinement of a hot plasma in the stellarator in the absence of current. Further, the scaling laws derived from ohmic heated plasma show that the electron thermal diffusivity improves as the current is reduced and that confinement is also improved. Thus considerable attention has been paid recently to experiments in auxiliary heating, with little or no plasma current. The following methods have been used in the CLEO and W VII A experiments: laser produced plasma (CLEO); electron cyclotron resonant heating (CLEO); neutral injection (CLEO, W VII A). The results of these experiments are described in the succeeding paragraphs.

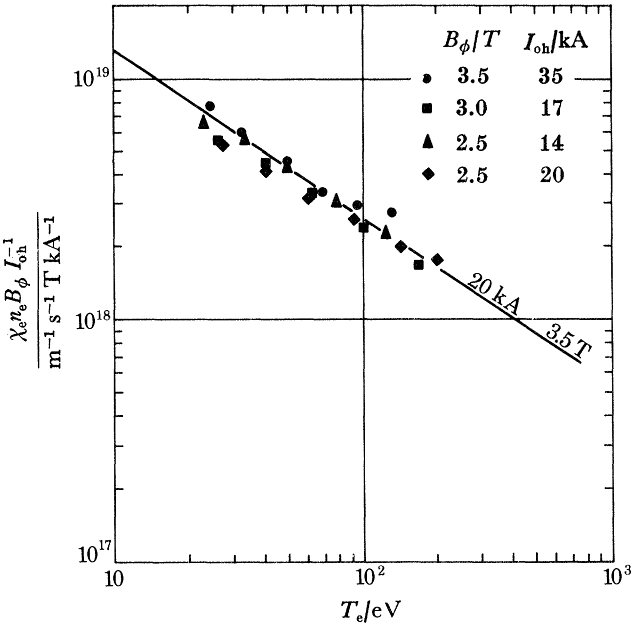

FIGURE 5. Electron thermal diffusivity χ_e multiplied by density n_e against electron temperature T_e for Wendelstein VIIA; $t_0 = 0.14$.

5. LASER PRODUCED PLASMA

Currentless plasmas have been produced in CLEO by irradiating a solid deuterium pellet, falling under gravity inside the torus, with radiation from a 1.5 kJ CO_2 laser. The resulting plasma was dominated by a high background of neutral deuterium, arising either from incomplete pellet ionization or interaction between the expanding plasma and the torus wall, causing large energy loss by charge exchange. Charge exchange can also cause particle losses. The plasma density decayed rapidly, over a period of 1–2 ms, compared with the time predicted by neoclassical theory of 100–500 ms (figure 6). It was observed, however, that the external transform did have an effect in that the efficiency of trapping (i.e. the initial density of confined plasma) improved with increasing current in the helical windings.

6. ELECTRON CYCLOTRON RESONANT HEATING

Plasmas have been produced in CLEO by ionizing and heating a background gas at the electron cyclotron resonance condition by means of microwave radiation from a klystron producing 15 kW of power at the frequency of 17.5 GHz (electron cyclotron resonance at 0.625 T). The resulting plasma has densities in the range of 1×10^{18} to 2×10^{18} m^{-3} and electron temperatures between 50 and 70 eV. The plasma energy (almost entirely in the electrons) is contained for approximately 1–2 ms in comparison with the time of about 10 ms estimated on the basis of neoclassical theory.

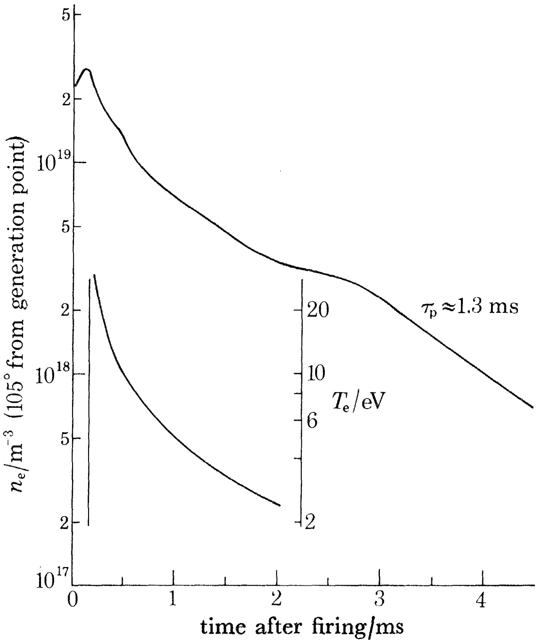

Figure 6. Density and electron temperature against time after firing for the laser-produced plasma in CLEO; $B_\phi = 1.3$ T, $I_1 = 10$ kA.

It is possible to assess, under reasonably controlled conditions, the effect of a small ohmic heating current on this plasma. This is shown in figure 7 in which the electron energy containment time is plotted against a parameter characterizing the drift of electrons in the applied electric field. At a high value of this parameter the containment is significantly worse, but a low current does not produce much change from that in a currentless plasma. Thus these results appear to confirm those in pure ohmic heated plasma; the confinement is improved at low current.

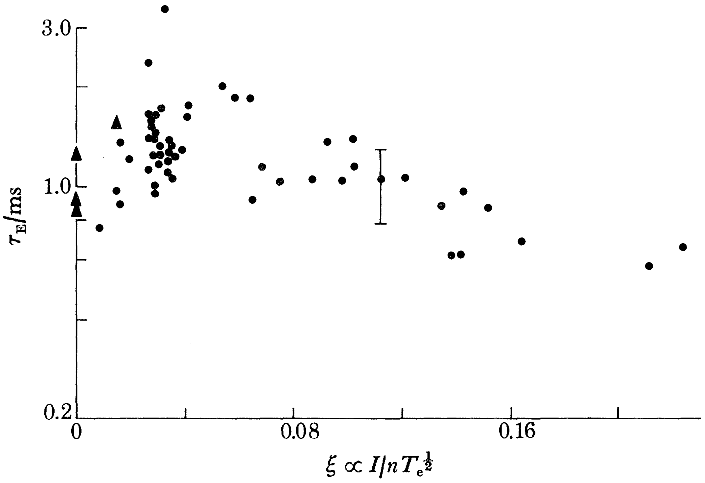

Figure 7. Energy containment time τ_E against drift parameter for an E.C.R.H. plasma in the CLEO apparatus; $B_\phi = 0.57$ T, $n_e = 2 \times 10^{18}$ m^{-3}, $T_e = 50$–70 eV.

7. Neutral injection

Both the W VII A and CLEO groups have used neutral injection heating to produce a currentless plasma in a stellarator. The beam of energetic neutrals is injected into a background plasma produced by weak ohmic heating, and during injection the plasma current is allowed to decay. Injection heating has also been used with a much higher plasma current, so that, as in the tokamak, the trapping of the beam depends on the poloidal field of the current.

The methods used by each group have some important differences.

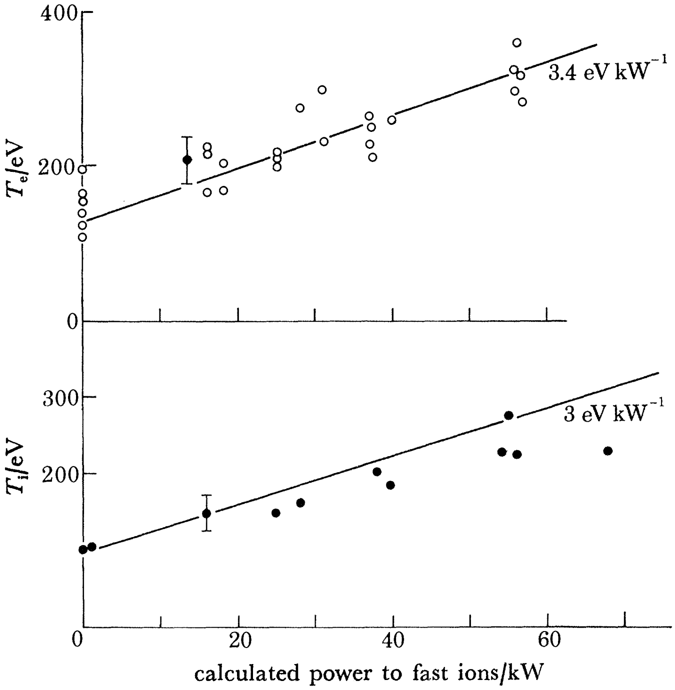

Figure 8. Electron and ion temperature against calculated power to the fast ions for neutral injected plasmas on CLEO; $B_\phi = 1.86$ T, $n_e = 2\times10^{19}$ m^{-3}, $P_{oh} = 7$ kW.

W VIIA system

Two injectors (eventually four) are used to give power of 500 kW (eventually 1 MW) at 30 kV, injecting hydrogen atoms into a helium plasma. Since access is limited the injection is at an angle of 6° to the normal to the torus, and a high target plasma density of 10^{20} m^{-3} has to be used for power to be deposited efficiently in the plasma.

CLEO system

This uses two injectors tangential to the torus with maximum power of 150 kW at 24 kV, injecting hydrogen atoms into a hydrogen plasma. Calculations show that for densities greater than about 2×10^{19} m^{-3} the power deposition should be effective.

CLEO results

In the first experiments, neutral beams were used to heat a low power ohmically heated plasma ($P_{oh} \approx 7$ kW). At modest densities (1×10^{19} to 2×10^{19} m^{-3}) a temperature rise of about a factor of two was seen for both electrons and ions, the rise being proportional to the calculated power transferred to the fast ions up to a level of about 70 kW, as shown in figure 8. At higher densities a plasma with β approaching 1% at a central density of $1.5 \times 10^{20}\ \mathrm{m^{-3}}$ and an electron temperature of 200 eV could be obtained, which gives a condition very close to the theoretical limit for stability. To ensure that the equilibrium magnetic surfaces were not displaced outwards by the high β it was necessary to apply a strong vertical field.

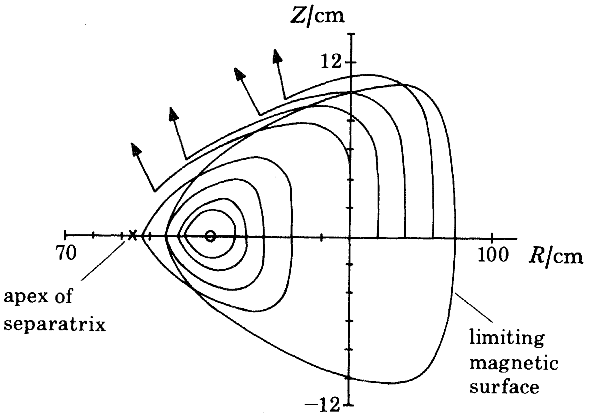

FIGURE 9. The drift surfaces of fast ions counter-injected into CLEO compared with the limiting magnetic surface; $B_\phi = 2.0$ T, $I_1 = 100$ kA, $E = 24$ keV.

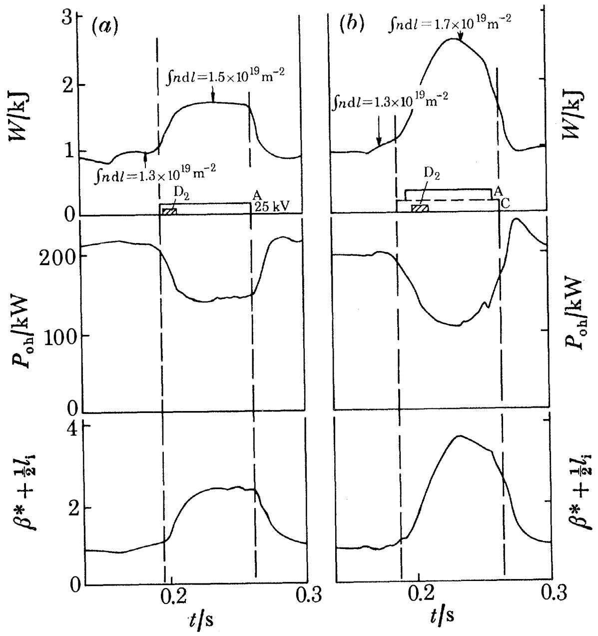

FIGURE 10. Oscillograms showing plasma energy W, ohmic power P_{oh} and plasma-β (plus internal inductance) for neutral injection into W VIIA for (a) one hydrogen injector (A) and (b) two hydrogen injectors (A, C). $B_\phi = 3.5$ T, $t_0 = 0.17$, $I_p = 25$ kA.

Efforts to reduce the ohmic current to zero while injecting neutrals have not been very successful. It is possible to sustain a plasma at a density of $10^{19}\ \mathrm{m^{-3}}$ by this means, but only at the low electron temperature of 20 eV. The explanation lies in the inefficient deposition of neutral power in the currentless plasma.

For an $l = 3$ stellarator in which the external transform is zero on the axis, the poloidal field which traps the fast ions has a maximum value near the plasma edge. The fast ion drift-orbits shown in figure 9 indicate that much of the ionized neutral beam power is therefore deposited in the plasma near the wall. In this region there are high losses from electron thermal conduction, from charge exchange with the high density of neutrals near the plasma edge and by radiation from impurity ions. The conclusion is that power deposition is not effective in CLEO without plasma current, which provides a poloidal field at the magnetic axis.

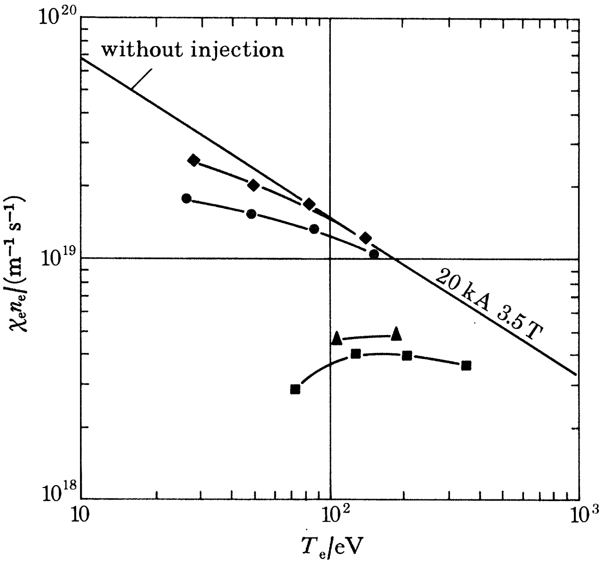

FIGURE 11. Electron thermal diffusivity χ_e multiplied by density n_e against electron temperature T_e for neutral injection and ohmic heating in Wendelstein VIIA. This graph is to be compared with figure 6. ■, ▲: $B_\phi = 3.2$ T, $I_{oh} = 20$ kA, $t_0 = 0.23$. ●, ◆: $B_\phi = 3.5$ T, $I_{oh} = 25$ kA, $t_0 = 0.17$.

W VII A results

In these experiments the level of ohmic power has been comparable with the neutral injection power to the plasma. The main effects of injection are seen in figure 10. During the injection pulse the plasma energy content increases and the ohmic power falls; this effect is increased when two injectors are switched on. There is an increase in electron temperature as measured by Thomson scattering. As the level of ohmic power is reduced, there is a proportionately larger increase in the plasma thermal energy. This is seen in figure 11 in which, as for the ohmic discharges of figure 5, the electron thermal diffusivity χ_e is plotted against T_e for several levels of ohmic current. At the lowest ohmic currents used, the electron thermal conductivity appears to be reduced. A possible alternative explanation lies in the uncertainty of calculating the fast ion power transferred to the plasma. If the losses of those particles mirrored in the local field variations are less than expected, the power deposited in the plasma could be greater than the calculated value. The prospects, however, seem to be encouraging for neutral injection into a stellarator, and further efforts are now being made to reduce the current to zero during the injection.

8. CONCLUSIONS

(i) In the earlier stellarator experiments it was shown that the external transform provided by the helical windings was effective in suppressing toroidal drift of plasma and assisting the confinement of currentless plasma.

(ii) Detailed energy balances, made more recently for ohmic heated plasmas, show that the energy containment time of ions in the stellarator is neoclassical, as in the tokamak. In the stellarator, however, the external transform assists the ion containment and also reduces ion thermal conductivity. Under conditions where electron losses are dominant, the scaling laws for energy containment are those appropriate to tokamaks, but with some improvement in the absolute value of electron thermal diffusivity χ_e. χ_e decreases as the current is reduced to a low value.

(iii) Heating of currentless plasmas by neutral injection appears promising, but the CLEO experience shows the need for the appropriate conditions, namely: (*a*) there is a clear advantage in using a large plasma target with clean walls and (*b*) there should be a non-zero rotational transform on the magnetic axis to encourage the deposition of power at the plasma centre.

Note added after symposium. The W VII A group has now (I.A.E.A. conference, Brussels, 1980) achieved hot currentless plasma by neutral injection.

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