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THE PERISTALTIC TOKAMAK

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A B S T R A C T

The Tokamak confinement system has the merit of simplicity, but the economic disadvantage (for a reactor) of pulsed operation. This paper shows that it should be possible to drive the plasma electrons continuously around the torus using travelling magnetic wave-like fields, thereby giving continuous operation. The ions require to be held stationary against the electron drag, and this may be achieved using another wave travelling in the opposite direction. A Tokamak reactor requires a total RF power input of about 100 MW at about 1 MHz: this input power is also sufficient to achieve ignition of the plasma.

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1. INTRODUCTION

The Tokamak confinement system (ARTSIMOVICH et al., 1969) is one of the more successful devices on the road to controlled fusion. It is simple both in concept and construction, and has produced the closest approach to a reactor-type plasma of any confinement system so far. However, it has the major disadvantage of pulsed operation because of the need to induce a toroidal electric current in the plasma, and it appears that the energy storage implied by the pulsed operation of a reactor will exact a considerable economic penalty on the operation of a fusion power station (CARRUTHERS et al., 1967). It is the purpose of this note to point out one method by which the Tokamak current can be maintained indefinitely, so that the device becomes a Direct Current Tokamak.

In what follows we have taken parameters for a possible Tokamak reactor given by GOLOVIN et al., (1969). This reactor has a minor plasma radius of 173 cm, the aspect ratio is 3, and the plasma density is 3×10^{14} cm^{-3}. To simplify the calculation we have departed from reality and assumed a plasma temperature (both ions and electrons) of 20 keV, uniform across the minor plasma diameter. With Golovin we take the safety factor q to be unity, so that the reactor operates at the Kruskal limit, and we take β_θ to be 3, the equilibrium limit. These last two values represent a considerable advance on the results achieved so far, but unless they can be achieved an economic Tokamak reactor is impossible (GOLOVIN et al., 1969). The azimuthal confining field we take as 40 kG, the required confinement time is 0.7 seconds, and we shall make calculations in cylindrical rather than toroidal geometry.

2. ELECTRON DRIVING

To maintain the plasma current in a Tokamak it is necessary to supply unidirectional energy to the electrons at a rate sufficient to overcome resistive loss. The electrons have thus to be driven around the torus, against what is in effect a frictional resistance, and the conventional method using a continuous electric field is limited to pulsed operation. We therefore propose the use of a travelling wave type of field driving electrons by a combination of inverse Landau damping from a longitudinal component of electric field and the magnetic analogue, transit time pumping, where the interaction between the electron magnetic moment and a travelling magnetic field gradient provides the driving force.

The action of the travelling magnetic field squeeze on the plasma within resembles the action of the travelling muscular squeeze in the intestines. We thus refer to the system as a peristaltic Tokamak.

This method acts by producing a small distortion of the electron velocity distribution by accelerating slightly slower electrons up to the wave phase velocity. The momentum thus gained by the electrons is distributed by collisions over the whole population, and the overall electron drift velocity, which is the plasma current, is thereby maintained. It is readily seen that the redistribution process conserves momentum but not energy, so that the energy which has to be injected into the system is greater than the resistive energy dissipation by the ratio of the wave phase velocity to the electron drift velocity.

Ultimately the ions in the plasma will acquire unidirectional momentum by continued electron collisions, but we shall show that the time required for this in a reactor is rather greater than the containment time: however, the ions will acquire sufficient velocity to cause an appreciable reduction in the effective current unless some means of stopping the ion drift is adopted. We describe a suitable method later.

The form of the travelling wave is somewhat uncertain. In a straight cylindrical system the compressional Alfven wave is the obvious choice, suitably excited by an array of coils surrounding the plasma. There is evidence however that this wave will not travel around a torus (CHUNG and ROTHMAN, 1967), so it may require to be simulated by an array of coils surrounding the minor circumference of the plasma, the array extending around the whole of the major circumference. This array would be fed with polyphase RF power to generate a travelling magnetic wave. In the absence of theoretical or experimental guidance we shall adopt a hybrid approach and assume that the wave field amplitude is the same as would be given by the array of coils, but that the wave phase velocity is given by the lowest Alfven mode in the plasma column.

This system of an array of coils surrounding a toroidal plasma resembles that used by THONEMANN et al., (1952), who drove currents of the order of 100 A in a small torus. However, the coupling mechanism proposed here is different, and will work with a collisionless plasma.

3. TOKAMAK PARAMETERS

With the given Tokamak parameters we find the required plasma current is 1.2×10^7 A. At 20 keV the Spitzer formula gives a plasma conductivity of 3.4×10^7 mho cm, so the total resistive dissipation within the plasma is

$$P_r = 1.5 \times 10^5 \text{ W}$$

and the dissipation per unit volume of plasma is

$$P_d = 4.8 \times 10^{-4} \text{ W cm}^{-3}$$

at a current density of 130 A cm^{-2}.

The Alfven velocity in the D-T plasma is 3.2×10^8 cm sec^{-1}, whereas the electron drift velocity is 2.7×10^6 cm sec^{-1}. Thus if the wave travelled at the Alfven speed, the total (high frequency) power input to the reactor would be 1.8×10^7 W. However, the wave on a plasma column surrounded by a metal wall will travel faster than the Alfven velocity.

This system is simple to analyse using cold plasma theory (STIX, 1962, p.88), the eigen-modes for the wave being given by the condition

$$J_1 (Xr) = 0 \text{ at the boundary}$$

where X is the radial wavenumber: for low frequencies we may use the approximation

$$X^2 = -(k^2 - k_0^2 S)$$

where k is the axial wavenumber, k_0 the free-space wavenumber ω/c for the wave of frequency ω, and S is a component of the dielectric tensor in Stix's notation. If we choose the plasma wavelength to be one fifth of the major circumference of the Tokamak, we have selected

$$k = 9.6 \times 10^{-3} \text{ cm}^{-1}.$$

For the lowest mode, the boundary condition is $Xr = 3.83$, so for the Tokamak we have

$$X = 2.1 \times 10^{-2} \text{ cm}^{-1}.$$

Also we find

$$S = 8.9 \times 10^3.$$

Thus this wave has

$$k_o = 2.45 \times 10^{-4} \text{ cm}^{-1}$$

and the frequency is 1.17 MHz. The phase velocity is 7.7×10^8 cm sec^{-1}, and with this phase velocity the RF input power to the plasma required to maintain the current is

$$P_T = 4.3 \times 10^7 \text{ W.}$$

4. ELECTRON PUMPING

The energy input to a Maxwellian electron distribution from the field of a travelling magnetic wave is given by STIX (1962, p.207) under the heading of Transit-time magnetic pumping. It has been pointed out (DAWSON and UMAN, 1965) that Stix's expression takes no account of finite electron pressure, which gives rise to a longitudinal electric field in the plasma. This electric field contributes an energy input (by conventional inverse Landau damping) which is equal to the input by magnetic pumping; we have therefore doubled Stix's power input rate to obtain

$$P_p = 2\pi^{\frac{1}{2}} \omega b^2 \, nkT \, x \exp -x^2$$

as the power input per unit volume of plasma.

We have assumed $T_e = T_i$ and $T_{\parallel} = T_{\perp}$ in this expression, and used ω for the wave frequency, b for the fractional magnetic field modulation and x for the ratio of wave phase velocity to electron thermal velocity.

For the Tokamak plasma, $nkT = 1 \text{ J cm}^{-3}$. With a wave phase velocity of 7.7×10^8 cm sec^{-1}, the factor x at 20 keV becomes 9.0×10^{-2}, so the exponential factor is unity. The wave frequency is 1.17 MHz, and the required power input 0.14 W cm^{-3}. Thus we find

$$b^2 = 6.0 \times 10^{-8}$$

so with a 40 kG confining field the RF magnetic field required is 9.8 G (peak).

Thus provided it is possible to generate a 1.2 MHz travelling magnetic wave whose amplitude is about 7 G rms, the plasma current in a Tokamak reactor can be maintained indefinitely.

5. ION MOTION

The unidirectional electron drift which is the current in the plasma will gradually transfer momentum to the ions through electron-ion collisions. Ultimately the ions will be drifting at the same speed as the electrons, there will be no net current flow, and the confinement will cease. It is evident, however, that the time required for this to occur will be about the electron-ion collision time multiplied by the ion-electron mass ratio. This time is found to be 1.1 seconds for the parameters chosen, so that with a confinement time of 0.7 seconds the ions will attain a directed velocity of just under one half the electron drift velocity. The effective current flow is thus halved, and obviously the confinement will fail.

To overcome this difficulty it would be possible to double the pumping field (to 14 G rms) and thereby drive twice the electron current in the plasma, using four times as much RF power to do so. An alternative and rather more subtle scheme would be to apply a second travelling wave in the opposite direction, whose phase velocity was equal to the ion thermal velocity. For the parameters chosen, this wave would have a frequency of 190 kHz. The power input at this frequency is obtained from the consideration that the momentum input to the ions at their thermal speed must equal the momentum input from electron collisions. Thus the required power input to the ions is

$$P_i = nmv_D \, v_{thi} \, \nu_{ei} \text{ per unit volume}$$

$$= 3.9 \times 10^{-2} \text{ W cm}^{-3}.$$

Using the magnetic pumping formula, we find that this power input requires an RF magnetic field whose amplitude is 4.5 G rms, and the total power input to the reactor at 190 kHz is 1.2×10^7 W.

This ion-stopping field would cause a small momentum input to the electrons in the wrong direction: the power input to the electrons is $(m_e/m_i)^{1/2}$ times the input to the ions, and so is 5.7×10^{-4} W cm^{-3}. This power represents a momentum input at the ion thermal speed (1.3×10^8 cm sec^{-1}), and is thus proportionally more effective than the same power injected at the wave phase velocity (7.7×10^8 cm sec^{-1}). To overcome this unwanted injection a further power of 3.4×10^{-3} W cm^{-3} must be injected at the electron driving frequency (1.2 MHz), so the total power at this frequency rises from 43 MW to 44 MW.

Similarly the electron driving field will act upon the ions. However, the factor x for this interaction is 5.9 so that the exponential term in the pumping expression is very small: the input power is negligible.

We thus finally require a total RF power of 56 MW to be injected into the plasma, of which 44 MW at 1.2 MHz drives the electrons and 12 MW at 190 kHz holds the ions. The Tokamak reactor can now operate continuously.

6. DISCUSSION

We have shown that within the limits of the approximations used it should be possible to maintain the current in a Tokamak reactor indefinitely. The price to be paid for this advantage is the continuous injection of 56 MW of RF power, which probably implies a supply of at least double this power to overcome the resistive losses in the array of coils surrounding the plasma (it seems possible to use one set of coils for both frequencies). All the power dissipated within the reactor appears as heat in the cooling system, and is thus partially recovered: the circulating power is still only a small fraction (~ 2%) of the reactor output electrical power.

The design (or even the possibility) of coils placed inside the vacuum wall of a reactor has to be examined: there are obvious structural and cooling problems. There are also insulation problems, for the voltage per turn required to generate a 7 G field over an area some 350 cm in diameter at 1.2 MHz comes to 50 KV rms. In the conventional Tokamak the plasma extends to the walls, but it seems unlikely that the RF coils could be immersed in plasma, so some means of restricting the outward extent of the plasma must be sought (Russian purists will object that the reactor is no longer a Tokamak).

Against these difficulties must be set one unexpected advantage. It is not difficult to show that conventional resistive heating is insufficient to ignite the Tokamak reactor, so that some additional means of heating will be required for start up. If it is assumed that the plasma loss represents the main energy loss during start up (rather than thermal conductivity, as we have remarked that the plasma will probably require to be isolated from the coils and vacuum wall), and that this loss occurs by classical processes so that the energy loss rate varies as $T^{5/2}$, it is easily shown that the maximum input energy required for ignition is about 0.13 W cm^{-3} at a temperature around 4 keV. Above this temperature charged particle heating becomes appreciable with the onset of thermonuclear reactions. Thus the RF input of 0.18 W cm^{-3} would be sufficient to ignite the reactor, so that we have not only provided continuous operation of the reactor but also solved the start-up problem.

We should remark that the values of q and β_θ taken are the optimistic reactor parameters. If we adopted values nearer present day achievements, we might set $q = 3$ and $\beta_\theta = 1$. This would imply an increase in plasma current by $\sqrt{3}$ times, and an increase in the static confining field by $3\sqrt{3}$ times. The ohmic dissipation would be tripled, and the electron drift velocity would increase by a factor of $\sqrt{3}$. The wave phase velocity will increase to 1.2×10^9 cm sec^{-1} at a frequency of 1.8 MHz for the same plasma wavelength. The RF power input required increases by a factor of 2.7, so the modulation index b increases by 1.65 times and, as the static field has increased, the coil current must be increased by 9.5 times. The inductive voltage increases to about 640 kV per turn, and the coil dissipation increases 70-fold. Thus it would appear that with present-day values of β_θ and q the Peristalic Tokamak is no less impracticable that the conventional pulsed system: the future prospect for both hinges on the achievement of $\beta_\theta = 3$ and $q = 1$.

7. CONCLUSIONS

If a Tokamak reactor is to be feasible, it must attain $\beta_\theta = 3$ and $q = 1$. If these parameters can be attained, it is theoretically possible to maintain the stabilizing current in the reactor indefinitely by driving both electrons and ions with travelling RF fields. The problems arising from the need to mount coils close to the plasma may be formidable, but if these can be overcome the RF power (56 MW) will be sufficient to ignite the plasma starting from temperatures which should be attained by ohmic heating.

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