Toroidal Fusion Devices Ignited by Ohmic Heating

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A toroidal configuration where the fusion ignition may be reached by ohmic heating alone is proposed. It is a hybrid between a tokamak and a diffused pinch. The reversal of a toroidal field in a diffused pinch is replaced by a doublet-like separatrix. Experimental results on mhd stability, especially limiting q -value of the doublet configuration will determine the validity of the scheme.

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INTRODUCTION

Design studies of large tokamak devices have indicated that the cost of the auxiliary heating equipment is a major part of the total cost. In addition, neutral beams of high energy or r-f heating of a high efficiency have yet to be developed. In contrast, the diffused pinch with reversed toroidal field could reach ignition by ohmic heating alone by virtue of its high current density. The trade-off is the difficulty associated with maintaining mhd-stability and the pulsed operation of the toroidal field.

In this note, the possibility of the overall optimumization by incorporating the advantages of two configurations, tokamak and diffused pinch is discussed. The goal is a toroidal device with a steady state toroidal magnetic field and with only ohmic heating.

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REQUIREMENT ON CURRENT DENSITY

To reach ignition, the ohmic heating must supply at least the plasma heat loss at ignition temperature, i.e.

$$\eta j^2 \geq 3nT/\tau \quad (1)$$

where η : resistivity, j : plasma current, n : density, T : temperature, and τ is the energy confinement time. The ignition condition is of course that $n\tau$ is larger than a number depending on the temperature. By rewriting Eq. (1), we obtain

$$j \geq n(3T\eta^{-1}/n\tau)^{1/2} . \quad (2)$$

For a typical set of numbers; $T = 10$ keV, $n = 10^{20} \text{ m}^{-3}$, and $n\tau = 5 \times 10^{20} \text{ m}^{-3} \text{ sec}$ we have $j \geq 10^7 \text{ amp m}^{-2}$.

Plasmas of a given density and a temperature can carry the current without causing turbulence or runaway electrons, if

$$j \leq \alpha n \sqrt{2T/m_i} , \quad (3)$$

where α is a numerical constant and m_i is the ion mass. The runaway will occur if $\alpha > \sqrt{m_i/m_e}$, m_e : electron mass. The acoustic turbulence may occur if α is significantly larger than unity.

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By combining Eqs. (2) and (3), we obtain the maximum temperature T_c above which there are no regimes of interest.

$$\eta(T_c) = \frac{3}{2} \frac{m_i}{n\tau\alpha^2 e^2} \quad . \quad (4)$$

For $\alpha = 3$, we have $T_c = 20$ keV.

The current density is also limited by mhd stability conditions. The safety factor q on the magnetic axis for a circular cross-section configuration is given by

$$q = \frac{2B_t}{\mu_o jR} \quad , \quad (5)$$

where R is the major radius and B_t is the toroidal magnetic field. By combining Eqs. (2) and (5), we obtain

$$q < \frac{2B_t}{\mu_o nR} \left(\frac{\eta n\tau}{3T} \right)^{\frac{1}{2}} \quad . \quad (6)$$

Or by introducing β defined by

$$\beta = 4nT\mu_o / B_t^2 \quad (7)$$

we have

$$q < \frac{4}{R} \left(\frac{\eta n\tau}{3\mu_o \beta n} \right)^{\frac{1}{2}} \quad (8)$$

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For a set of numbers customarily used for a tokamak reactor design, the value of q has to be smaller than unity. It is apparent that the ordinary tokamak can not be ignited by ohmic heating alone. The above condition also indicates that the maximization of q for stability and of β are in conflict.

MHD STABLE CONFIGURATIONS

The stability condition for axisymmetric tori requires that the safety factor q is the monotonic function of the minor radius. For a tokamak, q is an increasing function of radius, while for a diffused pinch q is a decreasing function of radius. Both configurations are mhd stable but use different stabilization methods.

In tokamaks, the stability near the axis is obtained by staying below the Kruskal-Shafranov limit, i.e. $|q| > 1$. Since $|q|$ is an increasing function near the edge of the plasma, the stability for the whole plasma is obtained by simply having a q -profile shown in Fig. 1.

In diffused pinches the stability near the axis can be obtained only by reversing the pressure gradient because of $|q| < 1$. The reversal of the pressure gradient in turn requires that the toroidal magnetic field decreases away from the axis. This causes $|q|$ to be a decreasing function of the radius. Since $|q|$ has to be an increasing function of the radius near the plasma edge, $|q|$ has to change its polarity in the plasma, as shown in Fig. 2. Thus a diffused pinch needs the reversal of the toroidal field.

For a configuration with unidirectional toroidal field and $|q| < 1$ to have a possibility of mhd stability, we must have $dp/dr > 0$ and $d|q|/dr > 0$ near the axis. The condition can be met if the current density peaks on the axis.

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Fig. 1--Profiles of safety factor and pressure in Tokamaks

Fig. 2--Profiles of safety factor and pressure in diffused pinches

We assume parabolic distribution for the toroidal field and the current density,

$$B_t \approx B_o (1 - r^2/r_1^2) \quad (9)$$

$$j \approx j_o (1 - r^2/r_c^2) \quad (10)$$

The condition $dp/dr > 0$ becomes

$$r_1^2 < q_o^2 R^2, \quad (11)$$

where q_o is the safety factor on the axis. Similarly the condition $d|q|/dr > 0$ becomes

$$r_2^2 < r_1^2/4 \quad (12)$$

However, the above condition will not be satisfied in ordinary tokamak discharges. The pressure gradient in tokamaks is determined by the temperature gradient because the density gradient is smaller than the temperature gradient. The current density in a steady state discharge is roughly proportional to the electric conductivity since the electric field is independent of the flux surfaces except the $1/R$ toroidal effect. Therefore the negative gradient of the current density and the positive pressure gradient are incompatible.

The above difficulty may be avoided by utilizing a noncircular cross section. In D-shaped or doublet configurations, the safety factor $|q|$ increases away from magnetic axis even with a uniform current density. Since the reversal of the pressure gradient requires only a few percent

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change in the toroidal magnetic field, a proper q profile can be maintained in a steady state possibly except very near the magnetic axis.

In this type of configuration, the confinement of pressure is done in the region where $|q| > 1$. If the $|q|$ value on the axis is much smaller than unity, it leaves a very narrow region where $|q| > 1$ for a D-shaped configuration. In contrast, the doublet configuration with its internal separatrix has the entire region outside of the separatrix available for the confinement. It may be that the triplet configuration is better for obtaining a large elongation with a very peaked current distribution.

The experiments in the past have confirmed some of the effects discussed above. The toroidal discharge experiments at General Atomic¹ have shown that the hollow pressure profile with a reversed toroidal field stabilizes the discharge. In Zeta,² the discharge with $|q| < 1$ goes into a turbulent state where the plasma pressure gradient almost vanishes but the magnetic configuration stays grossly stable albeit with fluctuations in the magnetic field. In tokamaks,³ the internal kink instability observed by soft x-ray detectors do not destroy the discharge but makes the central part turbulent.

The above considerations suggest that a doublet or a triplet configuration with a peaked current density may be the best choice. Outside the separatrix, the safety factor is larger than unity and the plasma is mhd stable. The region inside the separatrix where $|q| < 1$ could be made stable, if a hollow pressure profile is created. However it is probably impracticable to maintain the profile for many confinement times, since there is no sink for particles and energy on the magnetic axis. Therefore it is more

realistic to assume that the region becomes turbulent. The temperature, pressure, and current densities become homogenous due to rapid transport similar to the internal-kink unstable region in a tokamak. The profiles of the safety factor and the pressure is shown in Fig. 3.

If we approximate the elongated plasma cross section by a rectangle, the relation between the q value on the axis and at the limiter is given by

$$q_L = q_0 \frac{(1+\kappa)^2}{\pi\kappa} \gamma, \quad (13)$$

where q_L and q_0 are the safety factor at the limiter and on the axis, κ is the elongation factor and γ is the ratio of the current density on the axis to the average current density. The value of the safety factor on the axis is given by

$$q_0 = \frac{2B_t}{R\mu_0 j_0}, \quad (14)$$

where j_0 is the current density on the axis and the elongation factor has been neglected assuming a peaked current distribution. By combining Eqs. (13) and (14), we obtain

$$j_0 = \frac{2B_t}{R\mu_0} \frac{(1+\kappa)^2}{q_L \pi\kappa} \gamma. \quad (15)$$

The limiting value of q_L for a doublet configuration has not been tested experimentally. In Doublet II, the plasma current of 500 kA corresponding to $q_L = 2.8$ has been obtained without the current disruption.

Fig. 3--Profiles of safety factor and pressure of Doublets driven beyond $|q| < 1$ near the axis

The q -value of the region outside the separatrix is larger than q_L in Doublet, while the q -value inside the plasma is always less than q_L in tokamaks. Therefore it remains to be tested experimentally what is the lower limit on q_L . For the current density given by Eq. (14) to satisfy the condition given by Eq. (2), a small value of q_L , say 1.5 is required. However the actual value of q_L can be increased without affecting the current density by simply placing the limiter slightly inside, since the q -value increases toward the separatrix. The consequence is that the confinement has to be good because a narrower region is available for the confinement of the pressure and the heat.

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CONFINEMENT

So far it has been assumed that the confinement is good enough to reach ignition. Two questions are important for this type of approach. Firstly, will the turbulent region inside the separatrix affect the transport properties of the outside region? A partial answer may be the following. The tokamak experiments have shown that the transport rate increases when the internal kink mode is observed. The observed data may be fitted by assuming the turbulent transport (Bohm rate) inside the region $|q| < 1$ and the standard (pseudo-classical, etc.) elsewhere. It suggests that the rapid turbulent transport region is confined to the kinking region. Secondly, will the narrower region outside the separatrix result in faster transport due to a larger temperature gradient? The answer depends on the scaling of the transport, of course. If the transport rate is largely dependent on the poloidal magnetic field, for example, pseudo-classical or neo-classical, the overall confinement time is not affected greatly due to the increased poloidal field.

Since the true nature of the transport in tokamaks is largely unknown, the answer to this question is still speculative.

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