A D-H_e³ Fusion Reactor Based on a Dipole Magnetic Field

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ABSTRACT

An innovative fusion reactor suitable for D-H_e³ fuel is proposed, based on a dipole magnetic field produced by a simple one-turn coil with ≤ 16 T near-field intensity. The equilibrium plasma, whose phase-space density satisfies $\partial \hat{f}_0(\mu, J, \psi) / \partial \psi = 0$, where ψ is the flux function, has a steep enough pressure profile for an efficient fusion reaction yet is stable for low frequency instabilities to local beta exceeding unity. The semi-open field configuration is particularly suitable for D-He³ reactions.

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With nuclear fusion researchers expecting to demonstrate scientific breakeven in the near future, experts in reactor design are increasingly concerned about the use of deuterium-tritium (D-T) fuel. D-T fuel use introduces problems of excessive neutron production, tritium handling, and higher construction costs. Consequently, interest in aneutronic fusion based on D-He³ fuel is increasing. It is argued that although the D-He³ reaction requires an $n\tau$ (density-confinement time product) that is a factor of four larger and a temperature that is approximately the same factor as present designs, the reactor design can be significantly simplified because the fusion products are primarily charged particles.

A magnetic confinement scheme for D-He³ requires a configuration which can provide a stable plasma confinement for beta (ratio of plasma to magnetic field energy density) near unity with little or no anomalous transport loss. It is further desirable to have an open configuration so that the charged particles of the fusion product can be readily extracted for efficient energy conversion.

The dipole magnetic field configuration proposed here satisfies these requirements [1]. Figure 1 shows a schematic diagram of such a reactor. The magnetic field is produced by a properly shielded one-turn superconducting coil which is magnetically floated or mechanically supported in such a way that the confinement field lines do not cross the support. The plasma is produced primarily from a source at the wall via radially inward diffusion induced by RF fields with frequencies tuned at azimuthal drift frequencies, $\bar{\omega}_d(\mu, \epsilon, v)$ (≈ 1 kHz), of the plasma. Here, μ is the magnetic moment, ϵ is the particle energy,

and ψ the third adiabatic invariant is broken by RF fields.

Let us first discuss the plasma physics issue. The plasma produced here has an intrinsic phase-space density satisfying $\partial \hat{f}_0(\mu, J, \psi) / \partial \psi = 0$, where $J (= \oint v_{\parallel} d\ell)$ is the second adiabatic invariant. The corresponding equilibrium density, $n(\mathbf{r})$ perpendicular and parallel pressures $P_{\perp}(\mathbf{r})$ and $P_{\parallel}(\mathbf{r})$, are given, respectively, by

$$n = \int \hat{f}_0(\mu, J) \frac{B}{v_{\parallel} \oint \frac{d\ell}{v_{\parallel}}} d\mu dJ \propto \frac{B}{\ell} . \quad (1)$$

$$P_{\perp} = \int \mu B \hat{f}_0(\mu, J) \frac{B}{v_{\parallel} \oint \frac{d\ell}{v_{\parallel}}} d\mu dJ \propto \frac{B^2}{\ell} . \quad (2)$$

$$P_{\parallel} = \int m v_{\parallel}^2 \hat{f}_0(\mu, J) \frac{B}{v_{\parallel} \oint \frac{d\ell}{v_{\parallel}}} d\mu dJ \propto \frac{B}{\ell^3} . \quad (3)$$

where $\ell(B, \psi)$ is the length of the field line, $v_{\parallel}$ is the parallel component of the particle velocity, and the J conservation is assumed. For a low β plasma, $\mathbf{B}$ is approximately given by the vacuum dipole field,

$$\mathbf{B} = \nabla \psi \times \nabla \phi; \quad \psi = \frac{M \sin^2 \theta}{r} , \quad (4)$$

thus for a low β plasma, $n \sim r^{-4}$, $P_{\perp} \sim r^{-7}$, and $P_{\parallel} \sim r^{-6}$.

Collisions would isotropize the pressure. If the inward diffusion is made adiabatically, the plasma pressure would vary, $P \sim V^{-\gamma}$, where $\gamma (= 5/3)$ is the adiabatic constant and $V (= \int d\ell / B)$ is the flux tube volume with a constant total flux. The plasma pressure would then be $P \sim r^{-4\gamma} \sim r^{-20/3}$. Since the

fusion reaction rate is proportional to p^2 , the reaction occurs only near the core region even if the plasma is extended to a large radius. We note that the centrally peaked density and pressure profiles even for $\partial \hat{f}_0 / \partial \psi = 0$ are a unique consequence of the dipole field, i.e., in a toroidal field $\partial \hat{f}_0 / \partial \psi = 0$ gives a practically flat distribution (no confinement).

The equilibrium isotropic pressure distribution is given by $p(\psi)$ while $\psi \simeq M \sin^2 \theta / r$. Thus, if $P \sim r^{-20/3} \sim \psi^{20/3}$, the equilibrium plasma pressure is concentrated near the equatorial plane.

$$P(\theta) \sim \sin^{40/3} \theta. \quad (5)$$

Instabilities at $\omega \sim \omega_d$ can be studied by means of the phase-space distribution function $\hat{f}(\mu, J, \psi, \phi)$ which satisfies [2],

$$\frac{\partial \hat{f}}{\partial t} + \dot{\phi} \frac{\partial \hat{f}}{\partial \phi} + \dot{\psi} \frac{\partial \hat{f}}{\partial \psi} = 0, \quad (6)$$

where

$$\dot{\phi} = \left. \frac{\partial H}{\partial \psi} \right|_{\mu, J}, \quad \dot{\psi} = - \left. \frac{\partial H}{\partial \phi} \right|_{\mu, J} \quad (7)$$

$$H = \mu B + \frac{1}{2} m v_{\parallel}^2 + e \Phi. \quad (8)$$

We consider electromagnetic perturbations, $\delta \Phi$, $\delta \psi$, and δB . It is immediately clear from Eq. (6) that the corresponding perturbed distribution function δf is identically zero if the equilibrium distribution function $\hat{f}_0(\mu, J)$ does not depend on ψ . This fact guarantees that there are no instabilities based on wave-particle

interactions at $\omega \sim \omega_d$, and, thus, no anomalous cross ψ diffusion [3]. Furthermore, the electrostatic interchange instability is absent for this equilibrium [4,5],

However, magnetohydrodynamic (MHD) ballooning instabilities can still be excited since $\omega_* f_0 / \bar{\omega}_d = -\epsilon \tau_b \partial \hat{f}_0 / \partial J > 0$ with $\tau_b = \oint d\ell / |v_{||}|$, ω_* is the diamagnetic drift frequency, and $f_0 = f_0(\mu, \epsilon, \psi)$. In fact, a sufficient condition for stability is given by the following energy principle [6] which, for $\partial \hat{f}_0 / \partial \psi|_{\mu, J} = 0$, becomes [7].

$$\delta W = \delta W_I + \delta W_K, \quad (9)$$

$$\begin{aligned} \delta W_I = & \left[\left[\tau |\delta B - \frac{4\pi}{B^2 \tau} (\mathbf{e}_k \cdot \tilde{\nabla} P_{\perp}) \partial \psi|^2 \right] \right] + \left[\left[k_{\perp}^2 \sigma |\partial \delta \psi / \partial \ell|^2 \right] \right] \\ & + 16\pi^2 m \int d\mu d\epsilon \tau_b^2 \frac{\partial \hat{f}_0}{\partial J} \bar{\Omega}_d \overline{\Omega_K (v_{||}^2 / B + \sigma \mu / r) |\delta \psi|^2}, \end{aligned} \quad (10)$$

$$\delta W_K = -16\pi^2 m \int d\mu d\epsilon \tau_b^2 \frac{\partial \hat{f}_0}{\partial J} |\overline{\Omega_d \delta \psi + \mu \delta B}|^2, \quad (11)$$

$$[[...]] = \oint d\ell (...)/B, \quad \overline{(...)} = \left[\oint d\ell (...)/|v_{||}| \right] / \tau_b, \quad \mathbf{e}_k = \mathbf{k} \times \mathbf{e}_{||},$$

$$\tilde{\nabla} P_{\perp} = \nabla \psi \partial P_{\perp} / \partial \psi, \quad \tau = 1 + 4\pi \partial P_{\perp} / B \partial B, \quad \sigma = 1 + 4\pi (P_{\perp} - P_{||}) / B^2,$$

$$\tau_b = \oint d\ell / |v_{||}|, \quad \Omega_d = \mu \Omega_B + v_{||}^2 \Omega_K / B, \quad \Omega_B = \mathbf{e}_k \cdot \nabla \ln B, \quad \Omega_K = \mathbf{e}_k \cdot (\mathbf{e}_{||} \cdot \nabla) \mathbf{e}_{||},$$

while the equilibrium demands,

$$\tau \Omega_B + \frac{4\pi}{B^2} \mathbf{e}_k \cdot \tilde{\nabla} P = \sigma \Omega_K. \quad (12)$$

From Eq. (9), we see that for an odd parity mode or for an even parity mode with a rapid variation along ℓ , the field line bending term has a strong

stabilization effect and the beta limit due to the ballooning instability is approximately given by $\beta \simeq (\bar{\omega}_d/\omega_*) (\ell/\Delta\ell)$, where $\Delta\ell$ is the length of the field line over which the plasma is localized. We note that for a high beta equilibrium, the curvature near the equatorial plane is large, as indicated by Eq. (5). Thus, $\bar{\omega}_d/\omega_*$ is expected to be larger than unity, while $\ell/\Delta\ell$ is also much larger than unity. For an even parity mode with a slow variation along ℓ , $\delta W_k(>0)$ contributes to additional stabilizations while the field-line bending term gives stability to $\beta \simeq 0(1)$. Thus, the beta limit due to MHD ballooning is expected to exceed unity. These facts differ significantly from toroidal confinement schemes where generally $\bar{\omega}_d/\omega_* \sim a/R \ll 1$ while $\ell/\Delta\ell \simeq 1$. The stable plasma equilibrium in a dipole magnetic field even for $\beta \gg 1$ has, in fact, been observed in the Jovian magnetosphere [8].

Let us now discuss the reactor issue. The plasma is produced via RF-induced radial diffusion from a source located at the outer wall. The same RF field also heats the plasma due to μ and J conservations as the plasma diffuses inward where B increases. The position of the inner edge is controlled by the choice of the highest frequency ω_M of the RF such that $\omega_M = \omega_{dM}$, where ω_{dM} is the drift frequency of the innermost plasma. Since $\bar{\omega}_d$ does not depend on the particle mass, the inward diffusion warrants ambipolarity.

Let us define the dimension in the unit of the radius of the one-turn coil at the center. The fusion plasma may be confined at $2 \leq r \leq 4$ with the local $\beta \simeq 1$. For 4 T local field (or 16 T near field), this means there is a plasma with a temperature of 75 keV and electron density of $5 \times 10^{20} \text{ m}^{-3}$.

If we assume that the magnetic field in the high beta equilibrium decays as r^{-2} instead of r^{-3} , the density would decay as r^{-3} and the temperature as r^{-2} . In order to support a stable fusion plasma, a large volume of supporting plasma surrounding the fusion plasma is required. Since β decreases radially outward as r^{-1} , the supporting plasma has a lower beta and its density and temperature decay more like r^{-4} and $r^{-8/3}$, respectively. The supporting plasma also contains less total energy. At $r \sim 40$, the temperature and the density would become of the order of 300 eV and $5 \times 10^{16} \text{ m}^{-3}$. At this level of pressure, the plasma can be stably confined by the wall or by small cup fields, and be connected to the source with a slightly larger pressure at the wall.

Since the fusion cross section at the core temperature is only about a fraction of a percent of the coulomb cross section, in order to achieve ignition the central one-turn coil should have an opening in the center so that particles falling into the loss cone are not lost.

The power output due to the primary reaction,

becomes 18 MW/m³, while the plasma energy density is 12 MJ/m³. The self-sustained burn occurs for a confinement time of one second, which is easily achieved since anomalous radial diffusion is considered to be absent. We note that the synchrotron radiation loss is negligible because $\omega_{pe}/\omega_{ce} \simeq 30$.

The present scheme is particularly suitable for direct energy conversion because the charged particles of the fusion product can be guided out through

the open field lines near the axis by taking advantage of their discriminating large Larmor radius ($\simeq 20$ cm).

The RF start-up power is rather large and it may require some clever engineering design. One can utilize the whole chamber as a high Q cavity for an efficient coupling. Otherwise, the simplicity of this reactor structure is an attractive feature.

In summary, we have presented an innovative fusion reactor concept suitable for D-He³ fuel. The simplicity of the design, the semi-open field line configuration, and absence of low frequency micro- and macroscopic plasma instabilities make an aneutronic reactor potentially feasible.

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FIGURE CAPTIONS

Fig. 1. Schematic diagram of the Dipole Field Fusion Device.

Fig. 1

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