Self-Magnetic Fields

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Abstract

An ideal fusion reactor might be one in which the magnetic fields are self-generated by plasma currents, with little or no externally applied magnetic fields, with stability sustained by a highly conducting boundary. Three hypotheses are discussed: (1) *generation of a self-magnetic field, (2) evolution towards a minimum energy state, (3) increase of plasma density and temperature to thermonuclear conditions.*

Self-Generated Magnetic Fields

The large size and complexity of tokamaks stimulates a search for simpler configurations that could achieve the goal of sustaining a thermonuclear plasma. The present work considers the possibility energy input by electromagnetic waves, and confinement by a *self-generated magnetic field configuration* with the outward pressure sustained by a conducting shell.

Hypothesis 1: At high electromagnetic wave power input into a low-pressure gas inside a conducting chamber, a self-magnetic field could be generated.

Self-generation of magnetic fields is not unusual in conducting fluids. The earth generates its own magnetic field from a dynamo effect in a weakly conducting fluid. The sun and other stars generate their own magnetic fields on large spatial scales and time scales from a dynamo effect in plasmas at modest temperatures.

The growth rate of magnetic induction can be estimated from a combination of Faraday's Law and a generalized Ohm's law as

$$\partial \mathbf{B}/\partial t = \nabla \cdot\times \mathbf{u} \times \mathbf{B} \ - \nabla \times (\mathbf{J} \times \mathbf{B}/ne) \ + (1/en)\, \nabla T_e \times \nabla n - \nabla \times (\mathbf{R}_T/en) \\ - \nabla \times (\eta_{par}\mathbf{J}_{par} + \eta_{perp}\mathbf{J}_{perp}), \quad (1)$$

where

$$\mathbf{R}_T = -0.71\, n\, \nabla_{par} T_e \ - 1.5(n/\Omega_e\tau_e)\, \mathbf{b} \times \nabla T_e \quad (2)$$

is the thermal force, u = flow velocity, J = plasma current density, n = electron density, T_e = electron temperature (J), e = electronic charge, η = plasma resistivity, Ω_e = electron gyrofrequency, τ_e = electron collision time, $\mathbf{b}$ = unit vector parallel to **B**, and *par* and *perp* refer to vector components parallel and perpendicular to B. [Sudan 1994, changed into SI units]. In this equation several terms can contribute to magnetic field generation. A current density **J** induced by electromagnetic waves can contribute to the second and fifth terms on the right side. The third and fourth terms can be sources for a self-generated magnetic field. Thus, a self-magnetic field tends to be generated when the density and temperature gradients are not parallel or when there is a nonzero curl of the thermal force. For example, ripple of the initial bias magnetic field and non-uniform deposition of electromagnetic wave energy could tend to misalign the density and temperature gradients. Assume that the directions of the density and temperature gradients differ by an angle α, and that

$$\text{Density gradient source term} = (1/en)\nabla T_e \times \nabla n \_ \sin(\alpha)\, T_e/e\, L_n\, L_T \qquad (3)$$

where L_n , L_T = characteristic gradient scale lengths of density and temperature. The density dependence disappears, to a first approximation.

In a laser-produced plasma with T_e/e _ 100 eV, L_n _ L_T _ 10 microns, and α _ 5 degrees, the density-gradient source term is about 90 T/ns. Even with parallel density and temperature gradients, an instability could generate a magnetic field.[Bolshov et al. 1991] Several experiments have measured strong magnetic fields generated by absorption of electromagnetic radiation.[Vyas & Srivastava 1995, Bolshov at al. 1998]

Hasegawa et al. (1988) proposed "magnetically insulated inertially confined fusion" inside a spherical metal shell with magnetic fields induced by intense laser irradiation, Figure 1. A magnetic field of 100 T was measured in experiments with a CO_2 laser beam. Injecting a glass laser beam into a carbon-deuterium plasma confined in a gold shell, they observed $n\tau \geq 5\times10^{18}$ m^{-3} s, T $\geq$ 2 keV, and $\geq 10^8$ DD neutrons.[Nishihara et al. 1989]

Horowitz et al (1997) irradiated plasma inside a spherical metal shell with an intense circularly polarized laser beam. By an inverse Faraday effect, the beam created a toroidal current in the plasma, which induced an opposite current in the wall, and the currents induced axial magnetic fields inside and outside the plasma, in addition to the toroidal magnetic field created by the density gradient term. In experiments with 1.06 μm laser light at irradiances of 10^9 - 10^{14} W/cm^2, they measured axial magnetic fields from 0.05 -- 200 T. [Horowitz et al. 1998] These experiments suggest that, by controlling the polarization of the incident electromagnetic radiation, one can stimulate various magnetic field components in the plasma -- an axial magnetic field from circularly polarized light via an inverse Faraday effect and a toroidal magnetic field from the density gradient term.

Thus there are several mechanisms by which self-magnetic fields can be generated in plasmas in various regimes, including the density gradient term, the curl of the thermal force, the ponderomotive force, the inverse Faraday effect, and instabilities.

A laboratory plasma used for magnetic field generation might have n = 10^{18} m^{-3} and T_e = 100 eV. Table 1 compares the approximate parameters of such a laboratory plasma with those of the sun and of laser-generated plasmas.

The laboratory plasma lies between the sun and the laser-produced plasma in density, temperature, size, and time scale. For the laboratory plasma the density-gradient term might be the most effective mechanism to generate a magnetic field. For a hypothetical laboratory plasma with L_n , L_T _ 0.3 m, T_e/e _ 100 eV, and α _ 5 degrees, the density gradient source term is about 0.1 T/s, which is large enough to be of potential interest. Let us now consider how much power might be required to sustain a laboratory start-up plasma during magnetic field generation.

Input Power

During start-up the plasma would tend to stay cool, due to rapid heat conductivity and plasma instabilities, so enormously high powers might be required. This problem could be alleviated by addition of a weak bias magnetic field during start-up to inhibit heat losses. The field should be strong enough to facilitate heating a low-density plasma up to a fully ionized state in the presence of turbulence and MHD activity. A simple energy balance for a cylindrical plasma at equilibrium may be written

$$S \ \_ \ \nabla \bullet \mathbf{q} + P_{rad} , \qquad (4)$$

where S = heat source term, **q** = electron heat flux, and P_{rad} = radiation power loss, which is estimated to be much less than $\nabla \bullet \mathbf{q}$. Assuming that energy loss is dominated by turbulent Bohm diffusion with D_B _ T_{ev}/16B in a one-dimensional cylindrical approximation,

$$S \ \_ \ \nabla \bullet \mathbf{q} \ \_ \ 5\, n\, D_B\, \nabla T_e \ \_ \ 5\, n\, e T_{ev}^2 / 16\, B\, L_T \qquad (W/m^3) \qquad (5)$$

where D_B = Bohm diffusion coefficient, B = magnetic induction (T), $T_{ev} = T_e$ /e = electron temperature (eV), and e = electronic charge. For example, for a laboratory plasma with $n = 10^{18}$ m^{-3}, T = 100 eV, L_T _ 0.3 m, and initial bias field B = 0.01 T, we find S _ 0.17 MW/m^3, which might be feasible. A highly conducting shell might help to inhibit MHD instabilities during start-up, but this issue needs detailed study. The total input power requirement might be reduced if the magnetic field start-up region could be restricted to a small plasma volume, and then allowed to expand after the self-magnetic field got started. After sufficient magnetic field were generated, the start-up bias field could be turned off.

Minimum Energy State

Hypothesis 2: The start-up magnetic field would tend to tear and reconnect, evolving towards a minimum energy state.

Under some circumstances plasmas tend to evolve towards a minimum energy state described by the equation

$$\nabla \cdot \times \ B = \lambda B \qquad (6)$$

where B = magnetic induction and λ is the "Taylor parameter", which is spatially uniform in an ideal minimum-energy configuration.[Taylor 1986] Some experimental plasmas, especially spheromaks, tend to approximate this minimum energy state. A "dynamo" involving magnetic reconnection may adjust the magnetic field towards the minimum energy state.[Ortolani & Schnack 1993] Usually the plasma resistivity is high in the cool edge region, so the current density and λ are low at the edge. The minimum-energy state (uniform λ profile) is not fully achieved (the configuration is "nearly-minimum-energy"), and the gradient of λ drives turbulence that tends to move the plasma towards the minimum energy state.

Hypothetical Fusion Reactor

Hypothesis 3: After a nearly-minimum-energy-state low-density plasma is formed, its density and temperature could be gradually increased to thermonuclear conditions by continued injection of particles (pellets, gas, or particle beams) and of energy (electromagnetic waves or particle beams), with the plasma macroscopic stability preserved by a conducting boundary.

If these three hypotheses could be verified, if plasma stability and purity could be maintained, and if bootstrap currents could sustain much of the plasma current, then reasonable Q values might be attained, and a fusion reactor, Figure 2, might be feasible. A metal first wall could help to damp high-frequency disturbances, and the flux conserver outside the shield (probably a superconducting shell) could help to stabilize the plasma on longer time scales. The blanket/shield would be about a meter thick to attenuate the neutrons and gamma rays resulting from fusion reactions. Such a fusion reactor would be comparatively simple and low-cost. These hypotheses await testing by computer simulations or experiments. A longer article on this topic is available from the author.

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Table 1. Approximate parameters of sun, laboratory plasma, and laser-produced plasma.

Parameter	**Units**	**Sun (corona)**	**Laboratory plasma**	**Laser-produced plasma**
n	**m^{-3}**	10^{13}	10^{18}	10^{27}
T	**eV**	100	100	1000
R	**m**	10^{8}	1	10^{-4}
Time scale	**s**	10^{3}	1	10^{-9}
B	**T**	10^{-9} up to 0.3 (sunspots)	?	> 100

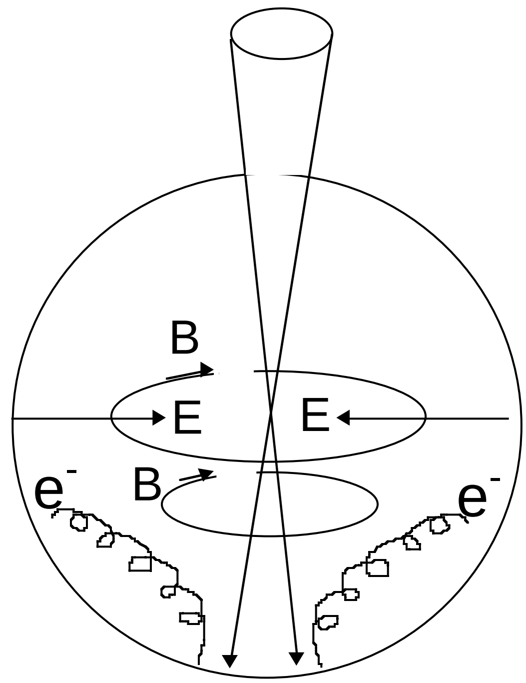

Figure 1. Generation of a magnetic field by a laser beam injected into a spherical metal shell. (After Hasegawa et al., 1988)

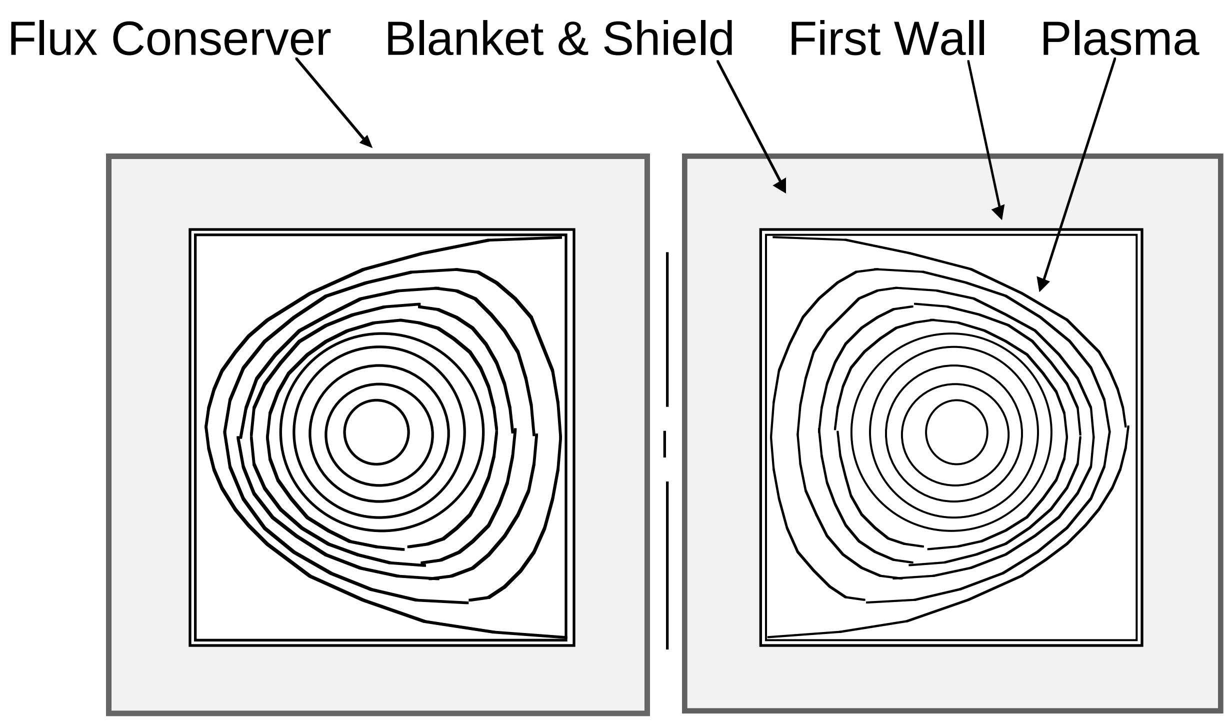

Figure 2. Hypothetical fusion reactor based on the use of self-generated magnetic fields. The ports for vacuum pumping, wave injection, and diagnostics are not shown.