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SELF-GENERATION OF MAGNETIC FIELDS

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The stars generate self-magnetic fields on large spatial scales and long time scales, and laser-produced plasmas generate intense self-magnetic fields on very short spatial and time scales. Two questions are posed: (1) Could a self-magnetic field be generated in a laboratory plasma with intermediate spatial and time scales? (2) If a self-magnetic field were generated, would it evolve towards a minimum energy state? If the answers turned out to be affirmative, then self-magnetic fields could possibly have interesting applications.

INTRODUCTION

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 generates its own magnetic field on large spatial scales and time scales from a dynamo effect. A laboratory plasma with $n = 10^{18}$ m^{-3} and $T_e = 100$ eV would be intermediate between the sun and a laser-produced plasma, which generate self-magnetic fields (Table 1).

Could a significant self-magnetic field be induced by high-power electromagnetic wave input into a laboratory plasma?

SELF-MAGNETIC FIELD GENERATION MECHANISMS

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

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

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, **b** = unit vector parallel to **B**, and *par* and *perp* refer to vector components parallel and perpendicular to B. [from Sudan,[1] changed into SI units]. The third and fourth terms on the right hand side of Eq.(1) 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.

If the directions of the density and temperature gradients differ by an angle α, then the density gradient source term

$$(\partial\mathbf{B}/\partial t)_{\nabla n} = (1/en)\nabla T_e\times\nabla n \approx \sin(\alpha)\, T_e/e\, L_n\, L_T, \quad (3)$$

where L_n, L_T = characteristic gradient scale lengths of density and temperature. In a laser-produced plasma with $T_e/e \approx 100$ eV and $L_n \approx L_T \approx 10$ microns, if $\alpha \approx 3$ degrees, then the density-gradient source term would be

about 50 T/ns. Self-magnetic fields on the order of 100 T have been observed in laser-plasma interaction experiments.

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

	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

There are at least five mechanisms by which self-magnetic fields can be generated:

1. Density gradient term, Eq. (1)

2. Curl of the thermal force, Eq. (1)

3. Ponderomotive force. The Ponderomotive effect occurs at very high power fluxes and is not likely to play a significant role in the laboratory plasma of Table1.

4. Inverse Faraday effect. Horowitz and coworkers irradiated plasma inside a spherical metal shell with an intense circularly polarized laser beam. 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.[2] An axial magnetic field was generated from circularly polarized light via an inverse Faraday effect and a toroidal magnetic field by the density gradient term. These experiments suggest that, by controlling the polarization of the incident electromagnetic radiation, one can stimulate various magnetic field components in the plasma.

5. Self-organization driven by turbulence. The total magnetic viscosity = $\eta + \eta_{turb}$. The kinematic magnetic viscosity η is always positive, but the turbulent magnetic viscosity η_{turb} becomes negative if the magnetic energy of small-scale turbulence exceeds the kinetic energy. A negative magnetic viscosity effect can lead to the appearance of a large-scale magnetic field growing from small-scale perturbations. Chechkin studied the phenomenon of a long-wavelength instability in a system of small-scale flows or vortices, with the energy of the small-scale turbulence being sustained by external means. When the small-scale magnetic field perturbation amplitude exceeds a critical value, a large-scale magnetic field can grow. This growth is analogous to the negative viscosity effect of the Kolmogorov flow instability in ordinary fluids. The negative magnetic viscosity effect can lead to amplification of the large-scale field and is a possible mechanism for explaining explosive magnetic phenomena in solar flares and tokamak disruptions. [3] [4]

Of the five mechanisms for generation of self-magnetic fields, the density gradient term and the self-organization driven by turbulence appear to be the most likely to be effective in the laboratory plasma of Table 1. Let us consider how these mechanisms might be induced.

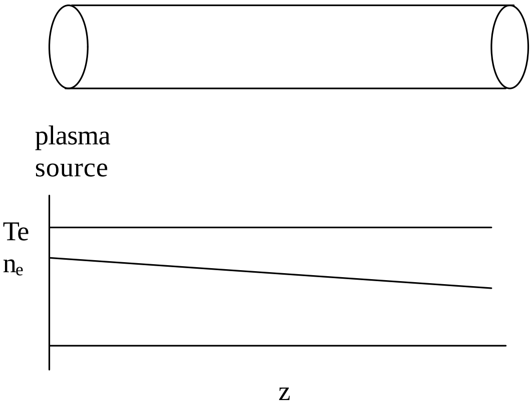

Figure 1. Axial density gradient due to non-uniform plasma source.

DENSITY GRADIENT TERM

Consider a long cylindrical plasma with a weak axial magnetic field, Figure 1. Rapid electron motion along magnetic field lines would tend to keep the electron temperature uniform in the z direction, so the electron temperature gradient would be essentially in the radial direction. The density gradient source term $(1/en)\nabla T_e \times \nabla n$ could be significant only if a substantial non-radial component of the density gradient could be produced. For example, a plasma density source at one axial location could cause an axial component of the density gradient. Assuming diffusive loss radially and axial flow at the ion sound speed $u_z \sim [(T_e+T_i)/M]^{1/2}$, the resulting density gradient term was estimated to be [5]

$$\partial B_\theta/\partial t \sim (1/ne)(\partial T_e/\partial r)(\partial n/\partial z) \sim (DT_e/ea^2 u_z). \quad (4)$$

For a plasma with D ~ 300 m^2/s, T_e/e ~ 10 eV, a ~ 0.3 m, and $u_z \sim 3 \times 10^4$ m/s, the density gradient term would be $\partial B_\theta/\partial t \sim 1$ T/s. Thus, a density gradient term could be induced by a non-uniform plasma source in this simplified model. The induced magnetic field, however, would also change the plasma behavior. A multidimensional, multifluid model, including momentum and energy conservation, collisions, turbulence, magnetic reconnection, wave-particle interactions, and wall interactions would be needed to derive an accurate description of these complex phenomena.

TURBULENCE

Very high power fluxes of electromagnetic waves might be required for brief periods of time in order to induce a high degree of turbulence that could trigger the negative magnetic viscosity phenomenon. The required power flux remains to be estimated as a function of plasma parameters. A lower bound is the input power required to sustain the plasma against radiation losses from heat conduction, bremsstrahlung and line radiation. It was estimated[7] that a plasma with a ~ 0.3 m, n = 10^{18} m^{-3}, T_e = 100 eV, 5 % carbon impurity, and initial bias field B ~ 0.01 T would have a power loss rate about 0.4 MW/m^3. Input power fluxes up to about 10 MW/m^2. have been injected into tokamak plasmas. Higher fluxes are conceivable for short periods of time. There are power flux limitations due to window damage and arcing of waveguides or antennas. The required input power 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.

If a self-magnetic field were generated, would it evolve towards a minimum energy state?

SELF-ORGNIZATION

Self-organization phenomena are observed in many areas of nature, such as Benard convection cells, snowflakes, autocatalytic chemical reactions, amoeba life cycles, materials science, electrical circuits, lasers, climate changes, entomology, and human society. [6] Therefore, it is natural to speculate that self-organization might occur in a plasma with regard to magnetic field generation and evolution towards a minimum energy state.

Under some circumstances plasmas tend to evolve towards a minimum energy state described by the equation $\nabla \times \mathbf{B} = \lambda \mathbf{B}$, where **B** = magnetic induction and λ is the "Taylor parameter", which would be spatially uniform in an ideal minimum-energy configuration. Spheromak plasmas, which tend to approximate this minimum energy state, have been generated by flux cores, by combined theta-Z pinches, by coaxial plasma guns, by conical theta pinches, by kinked Z pinches, and by electrostatic helicity injection. In view of their natural stability, it may be feasible to compress spheromak plasmas, and spheromak plasmoids have been injected across magnetic field lines into a tokamak. Often a "dynamo" involving magnetic reconnection adjusts the magnetic field towards the minimum energy state. 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.[7]

Various plasma self-organization phenomena have been observed experimentally. Plasma filaments formed by microwave discharges at high pressures tend to evolve towards "attractors." Whistler waves induced in low-density plasmas tend to evolve towards magnetic field configurations resembling three-dimensional Hill's vortices, sometimes forming knotted flux tubes. If excess plasma energy generated by magnetic reconnection is not removed, then a force-balanced equilibrium ($\nabla p = \mathbf{J}x\mathbf{B}$) may result, rather than a Taylor minimum-energy state.[8] Thermal conduction would tend to reduce the pressure gradient and perpendicular current, aiding the approach to a minimum-energy state.[9]

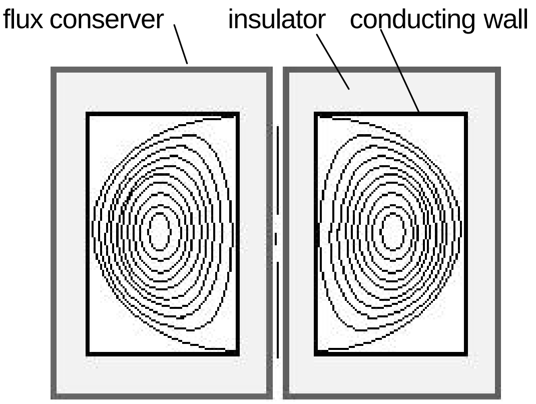

Figure 2. Compact toroid sustained inside flux conserver.

DISCUSSION

The questions of self-magnetic field generation and of possible evolution to a minimum energy state have been raised for consideration. If a self-magnetic field were generated and tended towards a minimum energy state, then it would be of interest to try to sustain the minimum energy plasmoid configuration while increasing the plasma density and temperature. A metal first wall could help damp high-frequency disturbances, and a superconducting flux conserver outside the chamber could help stabilize the plasma on longer time scales. Such a self-generated plasma configuration could possibly reduce the need for external high-field magnets and structural supports.

To study these issues a three-dimensional computer simulation including estimates of the optimum wave frequencies, polarizations, and possible cavity modes, could be helpful. Various experimental tests can be envisioned. For example, an extremely high flux of electromagnetic waves could be injected into a toroidal metal chamber surrounded by a high temperature superconducting (HTSC) flux conserver, as illustrated in Figure 2, with a non-uniform plasma source. If needed, a magnet coil inside the HTSC shell could provide a weak bias field to enhance start-up.

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