The Plasma Magnet for Deep Space Exploration And Radiation Shielding

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The Plasma Magnet

Two polyphase magnetic coils (stator) are used to drive steady ring currents in the local plasma (rotor) creating an expanding magnetized bubble. Expansion is halted by solar wind pressure is in balance with the magnetic pressure from the driven currents \((R \geq 10 \text{ km})\).

Applications:

- Multi-MW thruster leveraged from kW RF power
- Magnetic shielding of spacecraft from high energy solar particles
- Magneto-braking in magnetosphere of outer planets
- Electrical power generation from back emf on RF field coils from solar plasma flow (solar windmill)
- Target for beamed plasma power
The major difficulty in the original concept of course was the magnet mass.

The mass problem is solved by having the coil currents conducted in a plasma rather than a superconducting coil.

The question now becomes how to generate and sustain the currents.
How Plasma Magnet works

Rotating Magnetic Field (RMF) rotates at $\omega_{\text{RMF}}$

- $\omega_{ce} > \omega_{\text{RMF}}$ ($\omega_c = qB/m$)
  - Electrons rotate with the RMF

- $\omega_{ci} < \omega_{\text{RMF}}$
  - Ions don’t respond to RMF

- Electrons rotate among non-rotating ions
Surround spacecraft with plasma

- RMF drives current in the plasma
- Driven current results in a static magnetic field
- Static magnetic field acts as a barrier to the Solar Wind

Similar to Magnetic Sail, with the superconductor replaced by (much) lower mass plasma
How RMF is Generated

- Two orthogonal supplies
- Frequency determined by LC resonance of RMF Coil and “tuning” Series Capacitor (130 kHz)
FUNDAMENTALS OF THE PLASMA SAIL CONCEPT:

• Interaction of the plasma magnet with the solar wind similar to that of the planetary magnetosphere

• The challenge is how to form a sufficiently large magnetic bubble (on the order of the solar wind proton Larmor radius (~ 50-100 km)

• RMF driven currents assures both the inflation and large size

The density structure from MHD simulations

(a) on a global scale and
(b) near the region of the source

From G. Khazanov et al. AIAA JPC 2003

With $v_{sw} = 500$ km/s, $n_{sw} = 6$ cm$^{-3}$
20 km radius barrier receives a force of 4 N
Total thrust power $\sim 2$ MW
Plasma Expansion in the Presence of a Dipole Magnetic Field
(Winske and Omidi

FIG. 8. Time sequence of contours of magnetic flux for simulation with $B_d=100 B_0$ at (a) $\Omega_d t=0.0$, (b) $\Omega_d t=0.5$, (c) $\Omega_d t=1.0$, (d) $\Omega_d t=2.0$. 
MHD Calculation of Flowing Plasma Interaction with Magnetic Dipole (Nishida et al. JPC 2005)

Figure 5. Flow field around the Magnetic Sail (Attack angle = 0 degree).

Figure 6. Flow field dependency of the attack angle (Pressure contours and streamlines).
Thrust Vectoring and Steering with Dipole Tilt
Comparison of Kinetic and Fluid Treatment of Solar Wind - Plasma Sail Interaction

• In the kinetic case (a), the source particles are lost from the bubble in the transverse direction.
• In the fluid case (b), the source particles are lost predominantly in the downstream direction.

Changing relative plasma sail size allows for thrust vectoring.
Illustration of the Generation and Self-Inflation of the Plasma Magnet

- Rotating Magnetic Dipole field lines
- Steady dipole Field generated by Electrons moving Synchronously with RMF
- Plasma electrons
Simulation of Dynamo Effect with Fast Rotating Magnetic Fields

Rotation rate between the Ion and Electron Cyclotron Frequencies
Requires a ion cyclotron treatment beyond ideal MHD

Multi-Fluid Equations

\[
\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \mathbf{V}_\alpha) = 0
\]

\[
\rho_\alpha \frac{d\mathbf{V}_\alpha}{dt} = q_\alpha n_\alpha (\mathbf{E}_\alpha + \mathbf{V}_\alpha \times \mathbf{B}(\mathbf{r})) - \nabla P_\alpha - \left(\frac{GM_E}{R^2}\right) \rho_\alpha \mathbf{r}
\]

\[
\frac{\partial P_\alpha}{\partial t} = -\gamma \nabla \cdot (P_\alpha \mathbf{V}_\alpha) + (\gamma - 1) \mathbf{V}_\alpha \cdot \nabla P_\alpha
\]

Ion Cyclotron terms arise from full form of \( E + V \times B \)
Electrodynamics in Multi-Fluid Equations

\[
\frac{dV_e}{dt} = 0 \quad \Rightarrow \quad E + V_e \times B + \frac{1}{en_e} \nabla P_e = 0
\]

\[
n_e = \sum_i n_i, \quad V_e = \sum_i \frac{n_i}{n_e} V_i - \frac{J}{en_e}, \quad J = \frac{1}{\mu_0} \nabla \times B
\]

Modified Ohm’s Law:

\[
E = -\sum_i \frac{n_i}{n_e} V_i \times B + \frac{J \times B}{en_e} - \frac{1}{en_e} \nabla P_e
\]

Same as Hybrid Codes

These Corrections have increasing importance for Plasma Magnet as the ion skin depth approaches scale size of the antenna
Simulation System:

2 cm resolution out to > 5 m
Close up of the Instantaneous Rotating Magnetic Fields
Distant Instantaneous Rotating Magnetic Fields
Plasma Magnetic Sail Size Scales with Ambient Solar Wind Pressure
(constant force sail)

From this scaling, one could imagine moving in toward the sun until 20 km plasma sail is reduced to 0.2 m (100,000:1 compression).

- The solar wind pressure is ~ 2 nP at 1 AU
- The required pressure to compress down to the laboratory size is thus: $(10^5)^2 \times 2 \times 10^{-9}$ or ~ 20 Pa.
- Radial magnetic pressure from a 100 G magnetic field ~ 40 Pa
Plasma Magnet Experiments at the University of Washington

- External axial magnetic field exerts a radially inward pressure
- Pressure eventually halts the plasma expansion much like the solar wind will do in space.
- The much larger pressure keeps the plasma magnet compressed to the meter scale

Helmholtz pair produces external magnetic field (Solar wind surrogate)
Lab Plasma Magnet Parameters

- Plasma parameters at peak density (20 cm)
  \( T_{eV} = 6 \text{ eV}, \ n = 7 \times 10^{18} \text{ m}^{-3}, \ J = 70 \text{ kAmp/m}^2, \ B = 20 \text{ G} \)

  \[ \beta \approx 4.2 \ (420\%) \]

  \[ \nu_{ei} \approx 10 \text{ MHz} \]

  \[ \omega_{ce} \approx 350 \text{ MHz} \]

  \[ \nu_{ei} \ll \omega_{ce} \]

  \[ \omega_{ci} \approx 5 \text{ kHz} \]

  \[ \omega_{ci} \ll \omega_{\text{RMF}} \ll \omega_{ce} \]

- Operating in the RMF regime

  \[ R = 20 \text{ cm}, \ 4 \text{ Pa} \ (33 \text{ G}) \rightarrow \sim 2 \text{ N of total force on system} \]
Magnetic Field Generated by the Plasma Magnet Currents outside Antenna

Current flows initially inside the RMF antenna and expands outward at roughly Alfven speed.
Particle Confinement in the Plasma Magnet

$$\tau_N = \left( \frac{\text{total particles in bubble}}{\text{diffusion rate at boundary}} \right) = \int \frac{n \cdot d\text{Vol}}{D_\perp \frac{dn}{dr} \int dA}$$

$$(D_\perp = \frac{\eta_\perp}{\mu_0} \sim 1.5 \times 10^{-3} T_e(\text{eV})^{-3/2})$$

For lab PM ($a=0.1$ m, $T_e \sim 6$ eV) $\tau_N \sim 300 \ \mu\text{sec}$

Assume a density fall-off of $1/r^3$ (not critical but less than free-streaming $1/r^2$):

$$n(r) \sim n(a) \left( \frac{a}{r} \right)^3$$

$$N \sim 4\pi a^3 n_0 \ln \left( \frac{R_{\text{MP}}}{a} \right)$$

$$\tau_N \sim \frac{2\mu_0}{3 \eta_\perp \beta} \ln \left( \frac{R_{\text{MP}}}{a} \right) R_{\text{MP}}^2$$

At high $\beta (~1)$ and $T_e \sim 20$ eV and for antenna radius $a = 100$ m with sufficient current (density $n_a \sim 10^{16}$ m$^{-3}$) to inflate to a $R_{\text{MP}} = 40$ km bubble:

$$m_H N = 1.3 \ \text{g} \quad \tau_N = 4.5 \times 10^7 \ \text{s} \sim 15 \ \text{years}$$
Plasma Magnet Scaling

Energy in magnetic bubble

with a B dependence of $1/r \implies B_0 R_0 = B_{MP} R_{MP}$

$$E_B \sim \int_{R_0}^{R_{MP}} \frac{B(r)^2}{2\mu_0} \cdot d\text{Vol} = \int_{R_0}^{R_{MP}} \frac{B_0^2 R_0^2}{2\mu_0 r^2} \cdot 4\pi r^2 \, dr = \frac{\pi}{2\mu_0} B_0^2 R_0^2 R_{MP}$$

$$= \frac{\pi}{2\mu_0} B_{MP}^2 R_{MP}^3$$

Radius of magnetopause $R_{MP} = 30 \text{ km}$

Field at magnetopause $B_{MP} = 50 \text{ nT (500 } \mu\text{G) }$

$E_B = 84 \text{ kJ}$

(car battery $\sim 1 \text{ MJ}$)

Field Equivalent to solar wind pressure at earth radius

*Field Equivalent to solar wind pressure at earth radius
**Plasma Magnet Power Requirement**

- The expansion of the dipole is only limited by the ohmic power needed to maintain the structure from resistive dissipation.

Power required for a bubble of radius $R_{MP}$, the $1/r$ dependence in $B$ requires from **Ampere’s law** that

$$ j_0 = \frac{1}{\mu_0} \frac{dB}{dr} = \frac{B_0 R_0}{\mu_0 r^2} $$

$$ P_{RMF} = \int \eta j_0^2 \cdot dVol \approx \frac{\eta B_a a^2}{\mu_0^2} \int_a^{R_{MP}} \frac{4\pi}{r^2} dr \approx \frac{4\pi \eta}{\mu_0^2} B_a^2 a $$

The thrust power from the solar wind intercepted by the magnetosphere is approximately:

$$ P_{sw} = v_{sw} \cdot F_{MP} \sim v_{sw} \frac{B_{MP}^2}{2 \mu_0} \cdot \pi R_{MP}^2 $$

$$ \Rightarrow P_{sw} \sim \frac{\mu_0}{8\eta} v_{sw} a P_{RMF} = 4.6 \times 10^3 a P_{RMF} \quad (\eta \sim 20 \mu\Omega\text{-m}) $$
RMF Antenna Power Requirement

Recall: \[ P_{sw} = v_{sw} \cdot F_{MP} \sim v_{sw} \frac{B_{MP}^2}{2\mu_0} \cdot \pi R_{MP}^2 \]

For \( B \sim 1/r \): \[ C_{BR} = B_{MP} \cdot R_{MP} = B_0 \cdot R_0 = 1.5 \text{ mT-m} \]

\[ P_{SW} = C_D v_{SW} \frac{\pi}{2\mu_0} C_{BR}^2 \sim 6.3 \text{ MW} \]

Drag coef. \( \sim 5 \)

Dipole field is related to RMF by:

\[ \frac{B_0}{B_{RMF}} \sim \frac{R}{\delta} \sim \left( \frac{\mu_0 \omega}{2\eta} \right)^{1/2} R_A \]

Assuming one adjusts \( \omega \sim 1/R_A \) as the antenna is enlarged:

\[ P_\Omega = 9 \times 10^6 B_0^2 R_A^3 = 9 \times 10^6 C_{BR}^2 R_A \Rightarrow P_{SW} = 3.1 \times 10^5 \frac{P_\Omega}{R_A} \]
A Plasma Magnetic Sail (PMS) scales in principle to even higher powers depending on RMF power scaling.

Power and exhaust velocity sufficient for rapid manned outer planetary missions.

Current propulsion systems.

Comparison of Propulsion Systems
Integral Distribution of Particle Flux near Earth
(flux of particles with energies above the energy on axis)

-- aluminum skin of a spacecraft ~ 1 gm/cm²
Requirements for Radiation Shielding with a Plasma Magnet

For deflection of GeV proton one requires:

\[ B_r = 2B_0 \frac{a}{r} j_1(\lambda r) \cos \theta \]

\[ B_\lambda = -B_0 \frac{a}{r} \frac{\partial}{\partial r} (r j_1(\lambda r)) \sin \theta \]

\[ B_\phi = \lambda a B_0 j_1(\lambda r) \sin \theta \]

From previous scaling analysis:

\[ E_B = \frac{\pi}{\mu_0} B_0^2 a^3 \sim 2.5 a \text{ (MJ)} \]

\[ P_{RMF} = \int \eta j_0^2 \cdot dVol \approx \frac{4\pi \eta}{\mu_0^2} B_0^2 a^2 = \frac{40}{a} \text{ (MW)} \]

For \( a \sim 100 \text{ m} \):

\[ \Rightarrow P_{RMF} = 400 \text{ kW with charging time of 600 s} \]
Current Work on the Plasma Magnet Sail

Perform the critical experiments for concept validation

• Construct a sufficiently large dielectric vacuum chamber and install a plasma magnet as well as an intensified solar wind surrogate source.

• Perform a scaled test of the PM with and without the solar wind, and measure the thrust imparted to the PM.

• Measure all relevant plasma and field parameters for extrapolation to larger scale testing.

• Develop 2 and 3D numerical model for benchmarking against experimental results.
Concept Validation: Thrust Measurement And Scalability of Plasma Magnetic Sail

- Want to maintain plasma magnet size to observe expansion against Laboratory Solar Wind (LSW) $D_{\text{Antenna}} \sim 1/4 \ (0.4 \ \text{m}) - 0.1 \ \text{m}$
- With Constant force expansion/contraction need $\Rightarrow P_{\text{LW}} = P_{\text{SW}} = 2 \ \text{MW}$
- Want $\rho / R$ to scale for kinetic effects $\Rightarrow V_{\text{LSW}} \sim V_{\text{SW}} \sim 40 \ \text{km/s}$
Magnetized Cascaded Arc Source

Directed force from plasma gun can be substantial. From probe measurements: \((I_{dis} \sim 2 \, \text{kA}), \, v_s \sim 35 \, \text{km/s} \, (H)\)

\[
F_z = \frac{dN}{dt} m_i v_s = 0.15 - 0.25 \, N
\]
MW Plasma Source for Surrogate Solar Wind

Final assembly (minus Macor)

Aluminum disk with flux slits

Cross-section of boron nitride and molybdenum washers
Thrust Measurement System for Plasma Magnet Deflection by Lab Solar Wind Source

Interferometric method can detect displacement on the nanometer scale
Thrust Calibration Set-up for Plasma Magnet

Force between two loops with a current I

\[ F = \mu_0 I^2 \frac{a}{d} \]

- \( a \) = loop radius
- \( d \) = loop separation
- \( \frac{a}{d} \approx 20 \)

For 1 N force, \( I \approx 200 \) A

Current feed/support for RMF loops

Structural element Holding RMF antenna With embedded loop

Calibration loop (Independently supported)

Side view

Front view

I

0.1 to 10 msec

t
Summary

Results to Date:

• A plasma magnet has been generated and sustained in a space-like environment by a rotating magnetic field

• Sufficient current was produced in lab experiment for inflation of plasma sphere to 10s of km.

• Plasma and magnetic pressure forces observed to be reacted on to antenna coils through E-M interaction, Thrust measurement expt. is underway to confirm.

• Power, energy and fueling requirements for large scale Plasma Magnet should be minimal (~ kW, ~ kJ, grams)

• If confirmed in future scaling experiments, other uses such as GCR radiation shielding become feasible