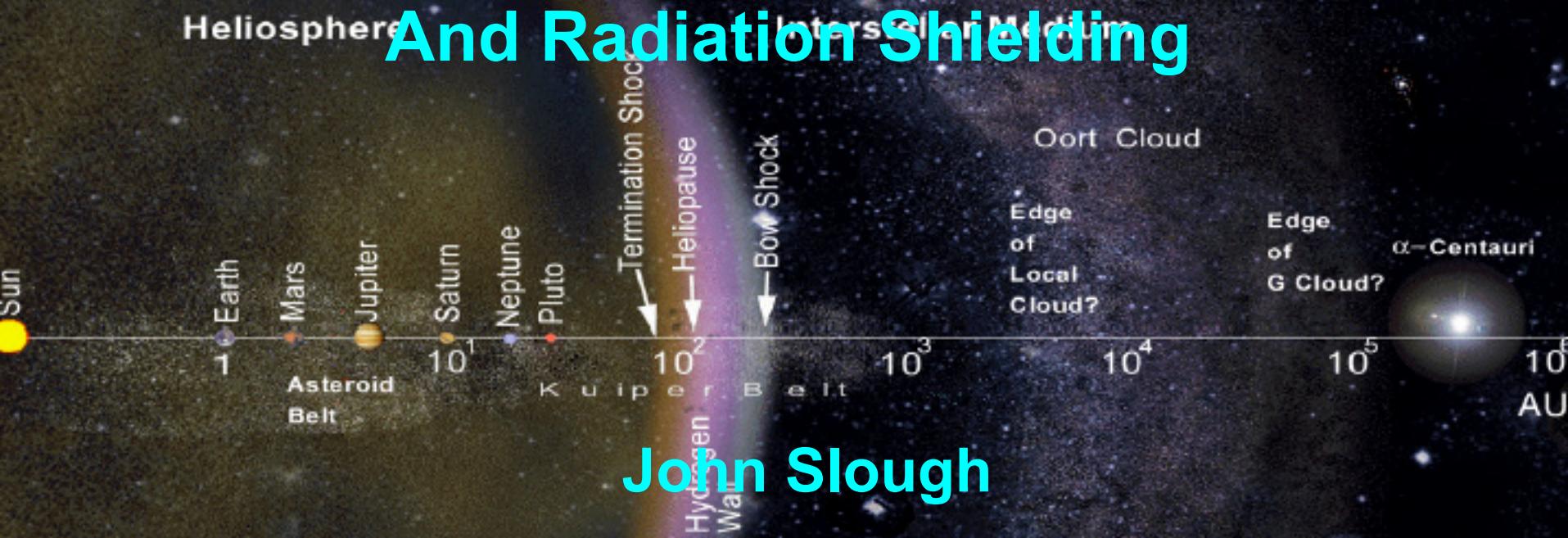


The Plasma Magnet for Deep Space Exploration And Radiation Shielding



John Slough

Collaborators:

Samuel Andreason, Louis Giersch, Robert Winglee

Research Institute for Space Exploration

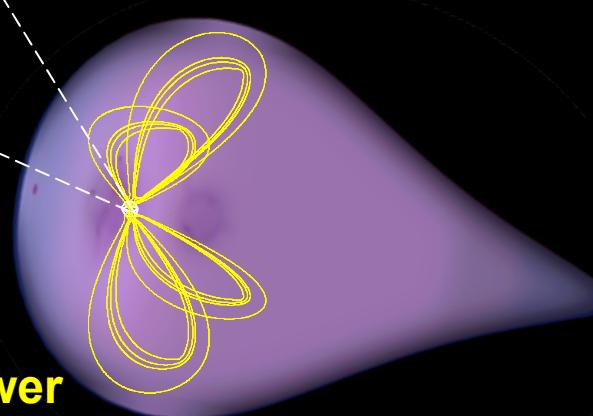
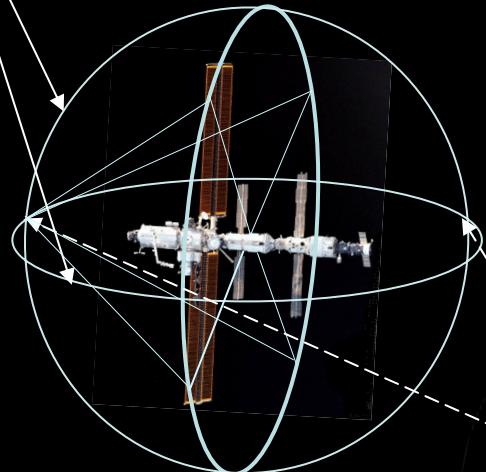
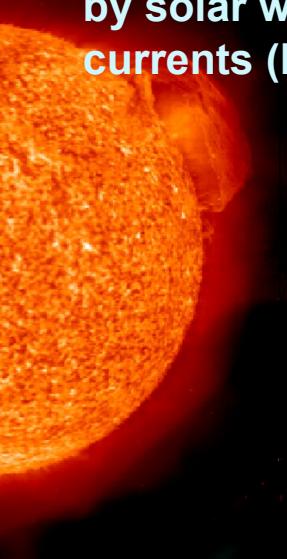
Plasma Dynamics Laboratory

University of Washington

NASA Interstellar Science & Technology Definition Team

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 ($R \geq 10$ km)

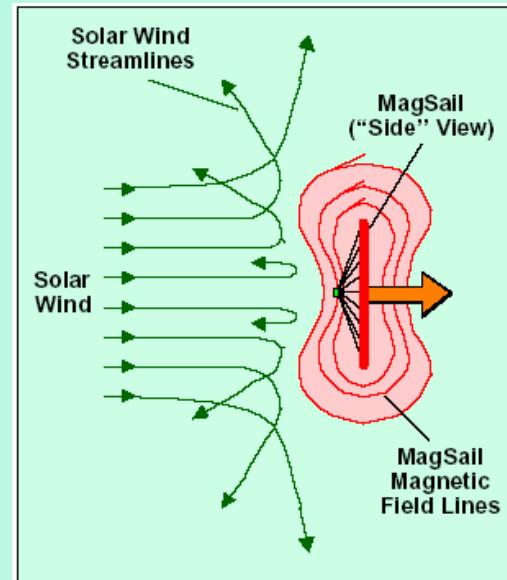
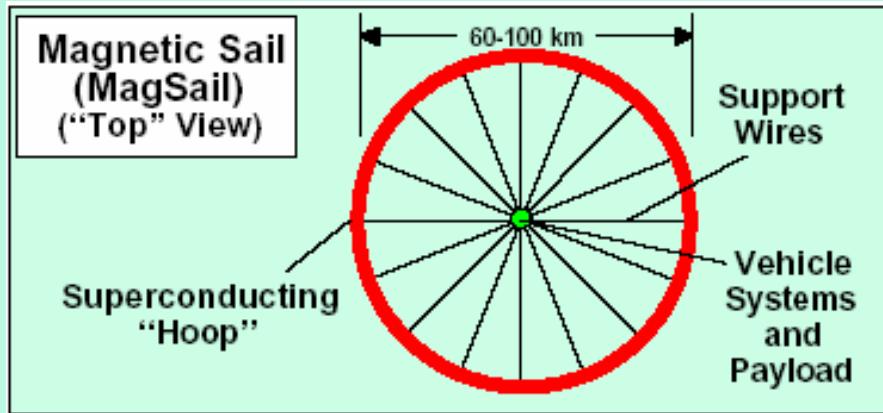


Applications:

- 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 Magnetic Sail

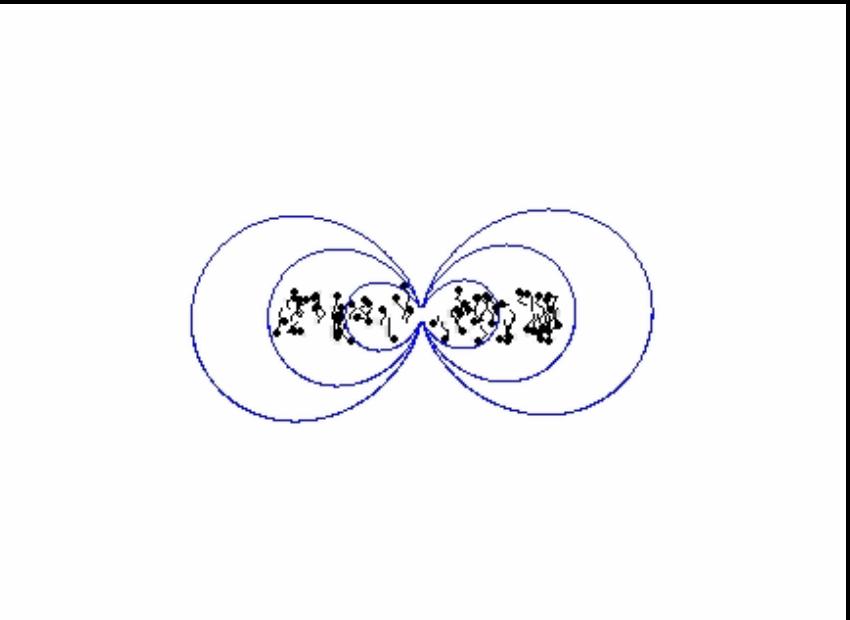
(Zubrin and Andrews, 1991)



- 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 ω_{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



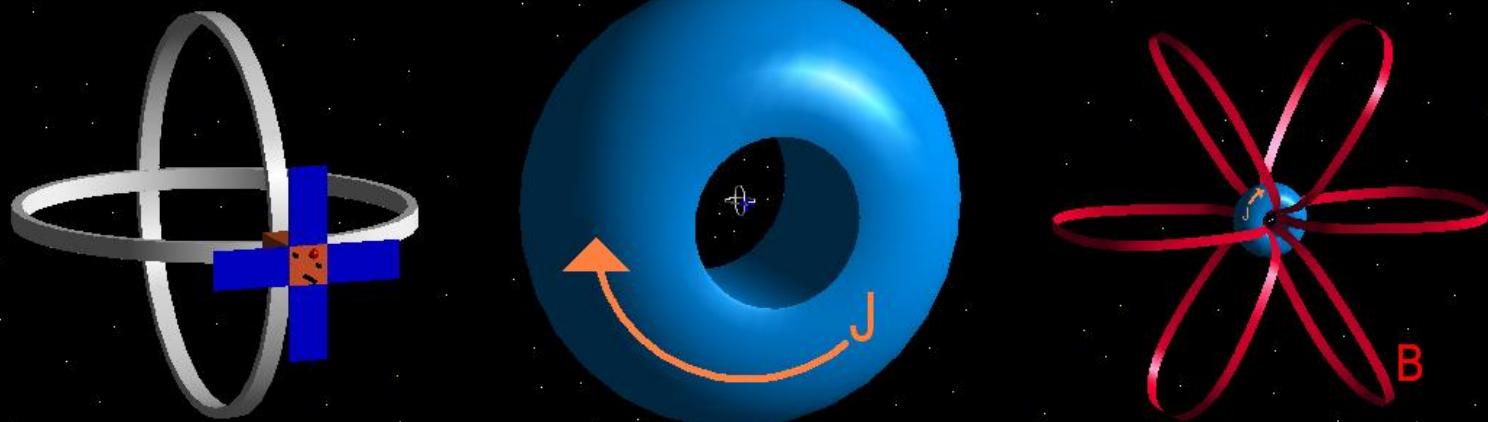
Surround spacecraft with plasma

→ RMF drives current in the plasma

→ Driven current results in a static magnetic field

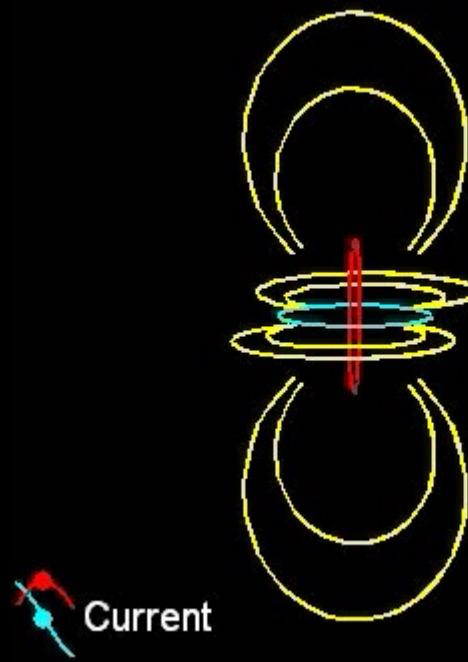
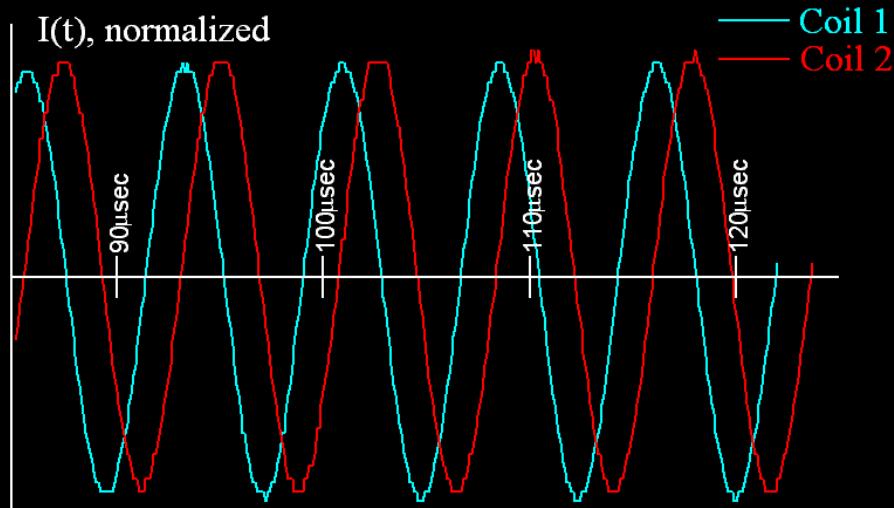
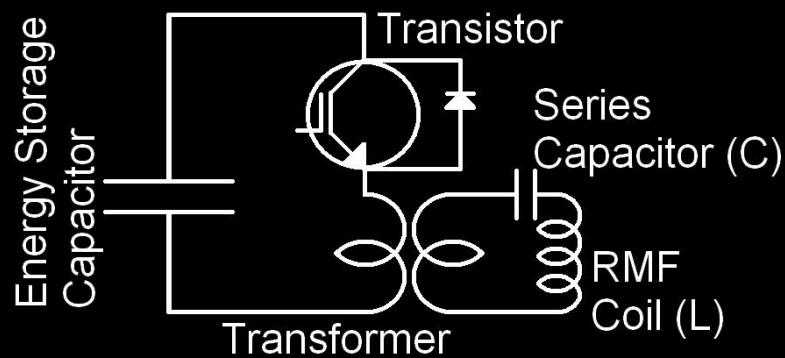
→ Static magnetic field acts as a barrier to the Solar Wind

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



How RMF is Generated

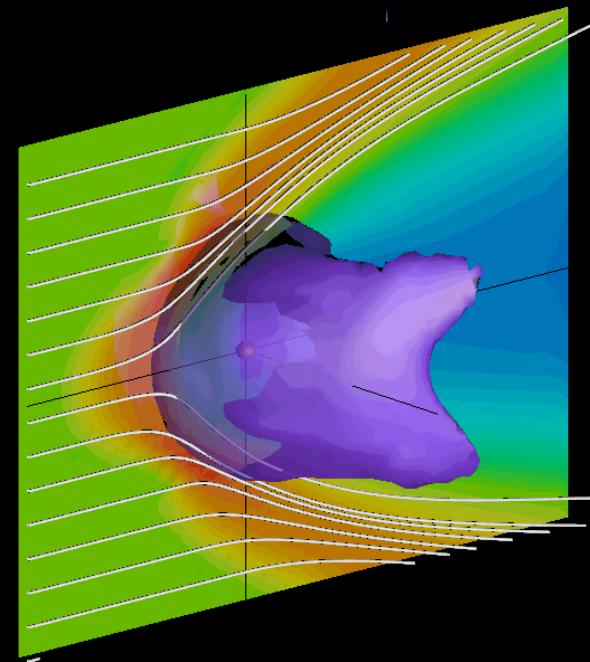
- Two orthogonal supplies
- Frequency determined by LC resonance of RMF Coil and “tuning” Series Capacitor (130 kHz)



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

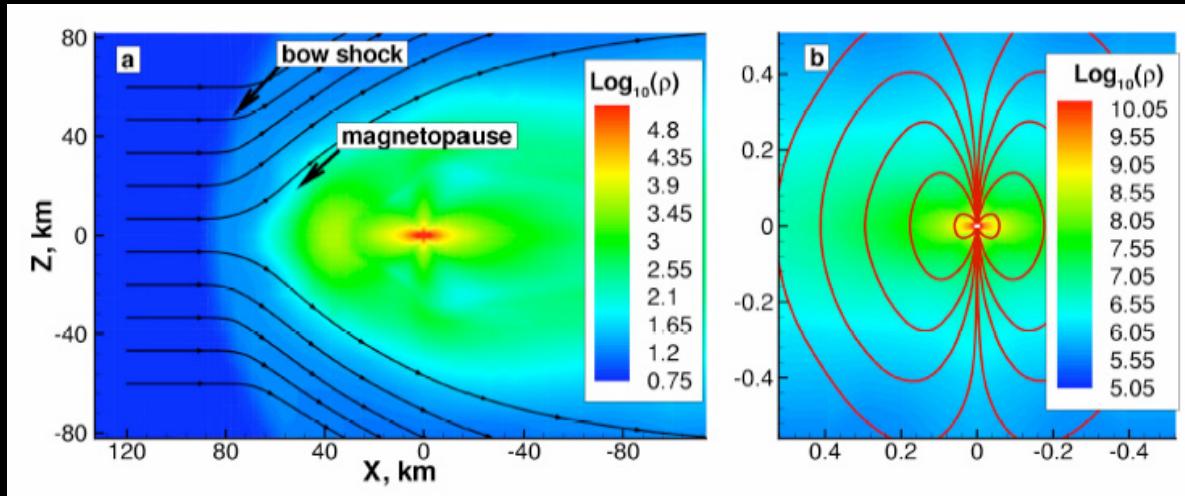
Mini-Magnetospheric Plasma Propulsion



From R.M. Winglee, J. Slough,
T. Ziemba, and A. Goodson.
J. Geophys. Res., 105, 9, 21,077, 2000

PLASMA SAIL CONCEPT: MHD AND KINETIC STUDIES

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 $v_{\text{sw}} = 500 \text{ km/s}$, $n_{\text{sw}} = 6 \text{ cm}^{-3}$

20 km radius barrier receives

a force of 4 N

Total thrust power $\sim 2 \text{ MW}$

Plasma Expansion in the Presence of a Dipole Magnetic Field

(Winske and Omidi
Phys. Of Plasmas, 2005)

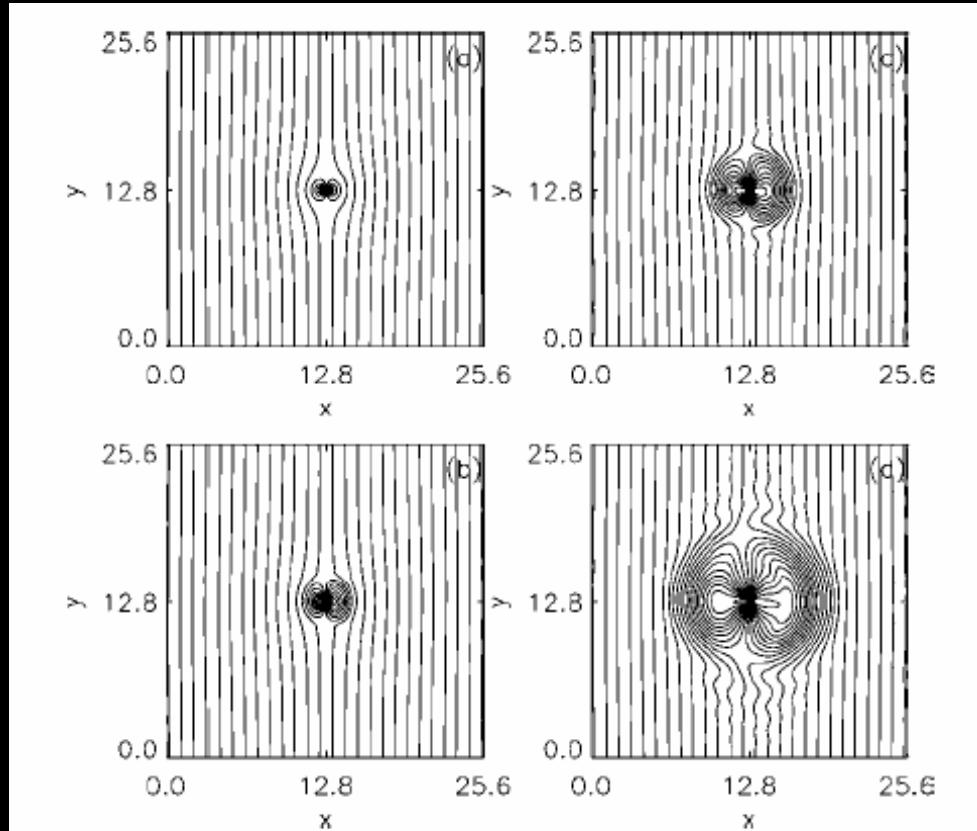


FIG. 8. Time sequence of contours of magnetic flux for simulation with $B_d = 100 B_0$ at (a) $\Omega_i t = 0.0$, (b) $\Omega_i t = 0.5$, (c) $\Omega_i t = 1.0$, (d) $\Omega_i t = 2.0$.

MHD Calculation of Flowing Plasma Interaction with Magnetic Dipole (Nishida et al. JPC 2005)

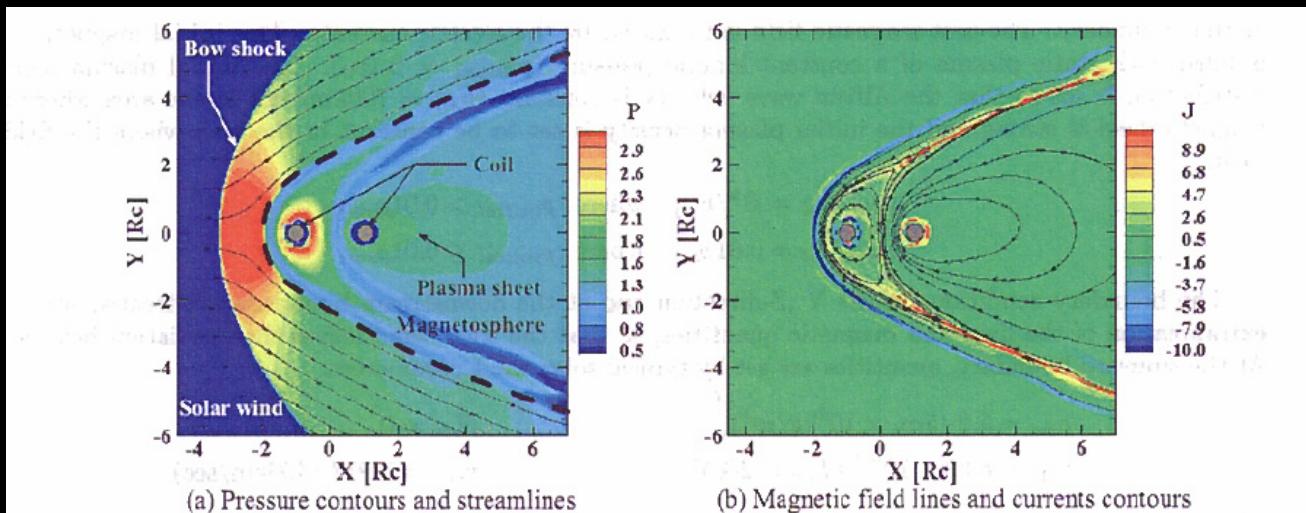


Figure 5. Flow field around the Magnetic Sail (Attack angle = 0degree).

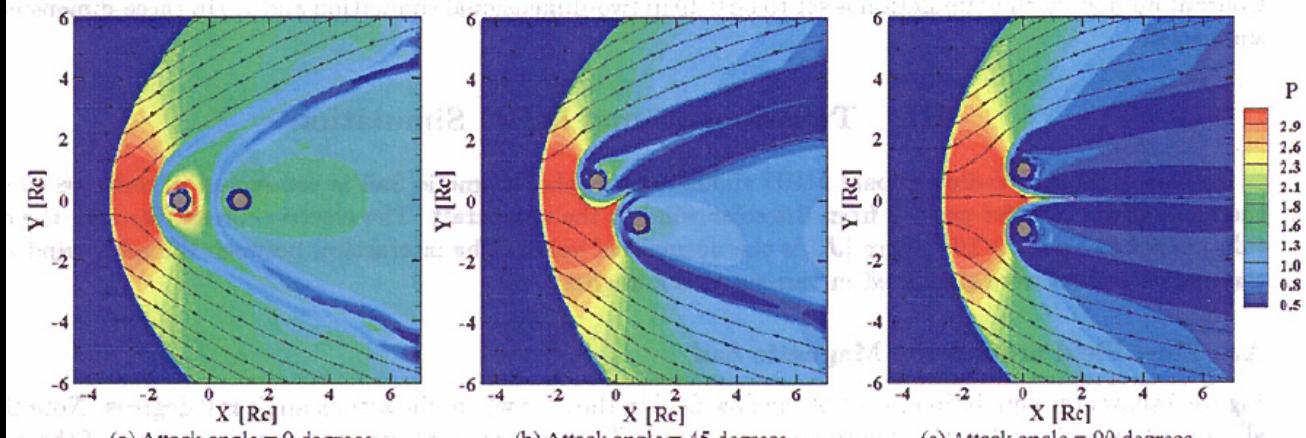
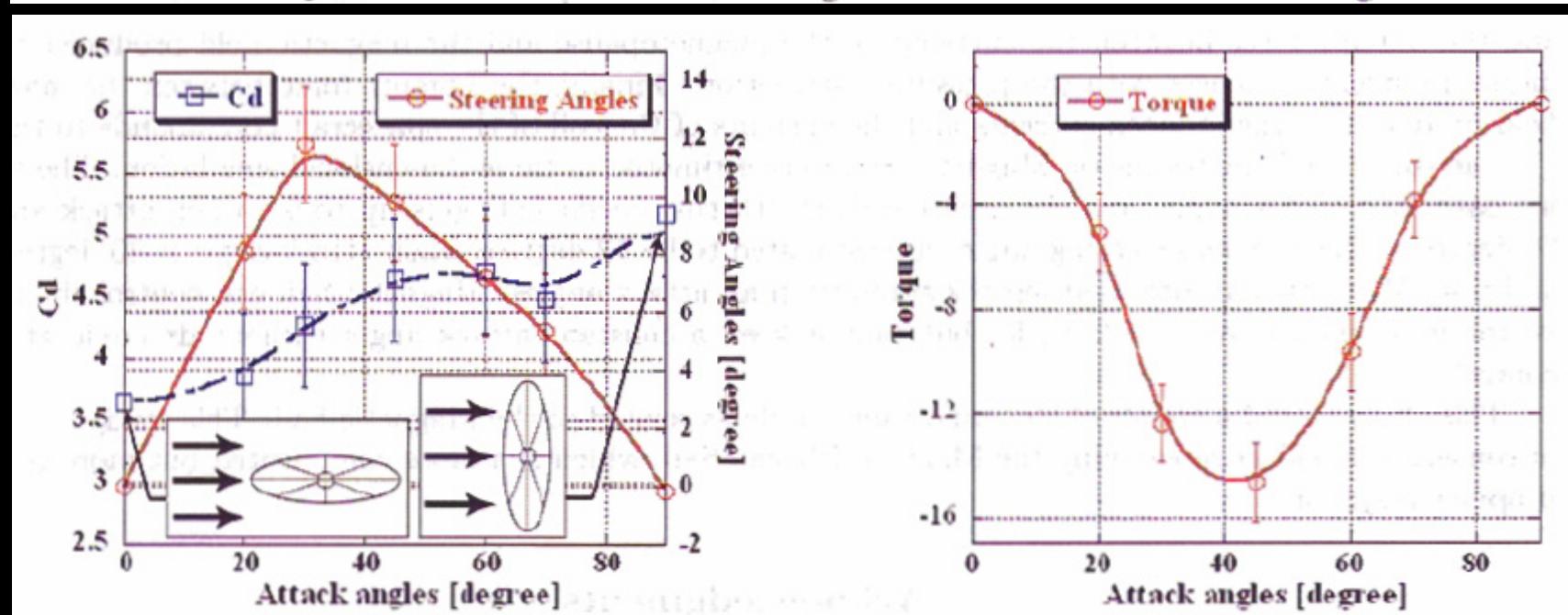
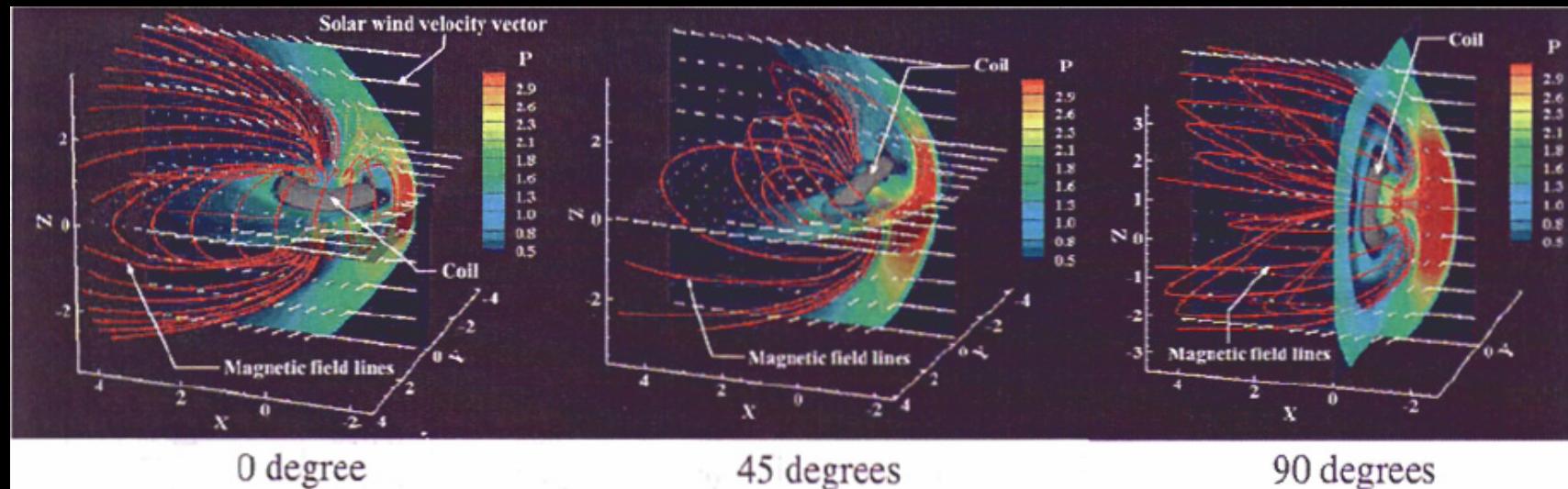
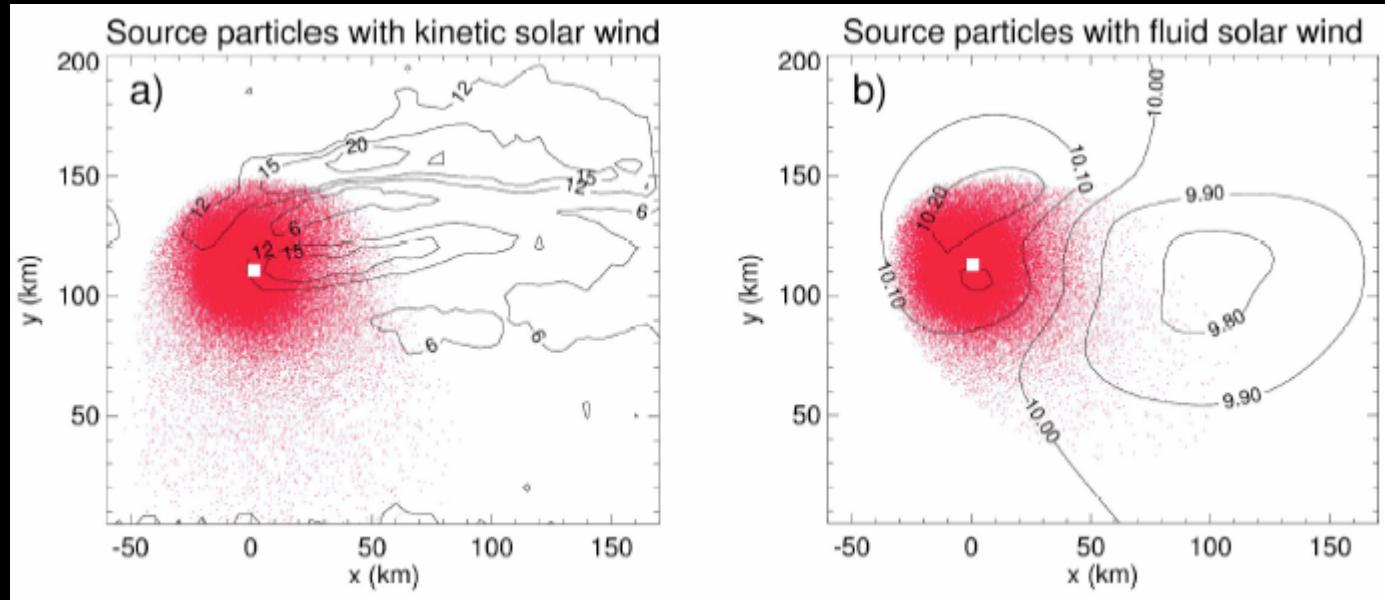


Figure 6. Flow field dependency of the attack angle (Pressure contours and streamlines).

Thrust Vectoring and Steering with Dipole Tilt



Comparison of Kinetic and Fluid Treatment of Solar Wind - Plasma Sail Interaction

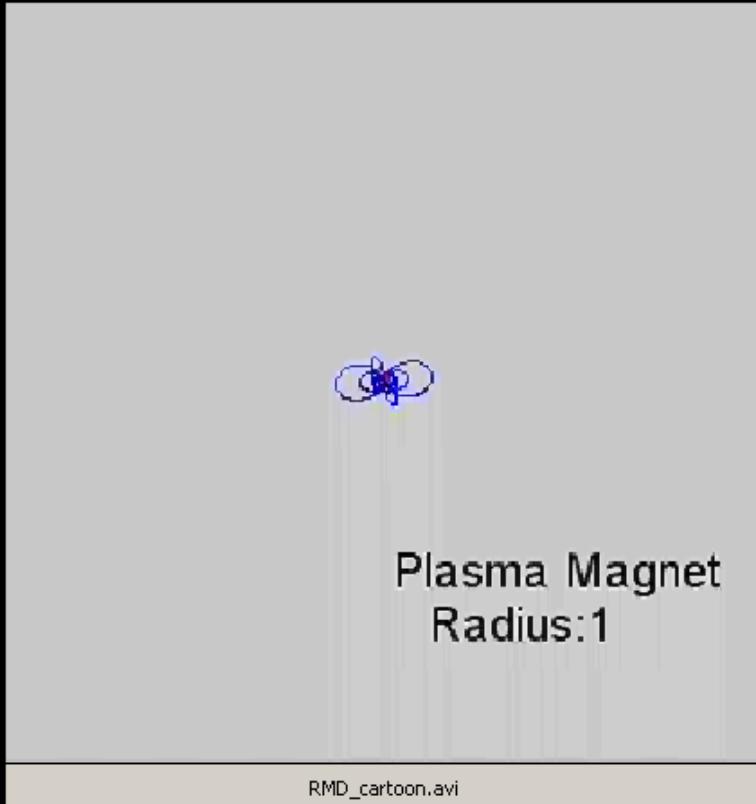


$$F_x \sim 3.4 \text{ N}$$
$$F_y \sim 1.4 \text{ N}$$

- 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

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

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

$$\frac{\partial \mathbf{P}_\alpha}{\partial t} = -\gamma \nabla \cdot (\mathbf{P}_\alpha \mathbf{V}_\alpha) + (\gamma - 1) \mathbf{V}_\alpha \cdot \nabla \mathbf{P}_\alpha$$

Ion Cyclotron terms arise from full form of $E + VxB$

Electrodynamics in Multi-Fluid Equations

$$\frac{dV_e}{dt} = 0 \quad \rightarrow \quad E + V_e \times \mathbf{B} + \frac{1}{en_e} \nabla P_e = 0$$

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

Modified Ohm's Law:

$$\mathbf{E} = -\sum_i \frac{n_i}{n_e} \mathbf{V}_i \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{en_e} - \frac{1}{en_e} \nabla P_e$$

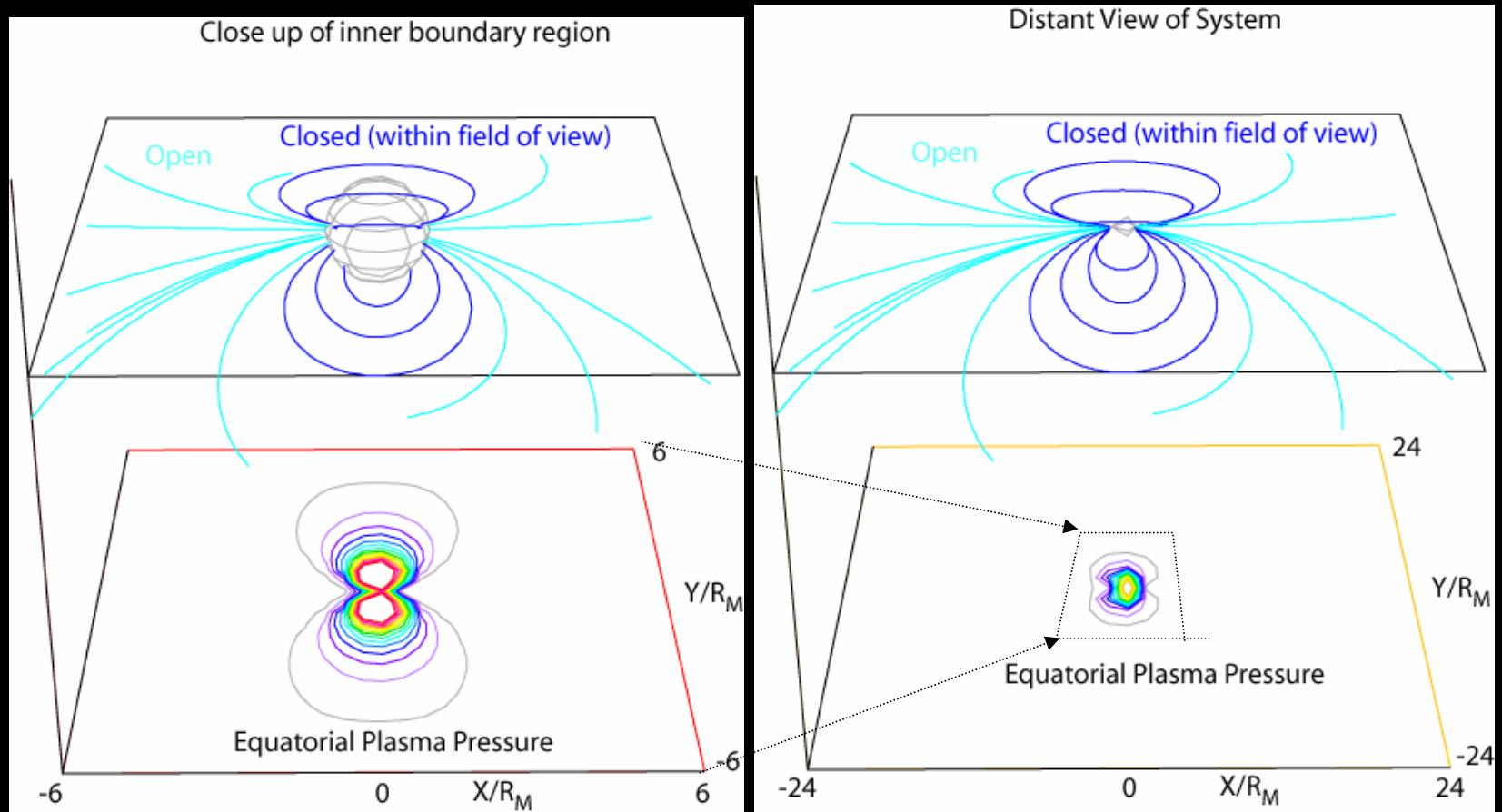
Same as Hybrid
Codes



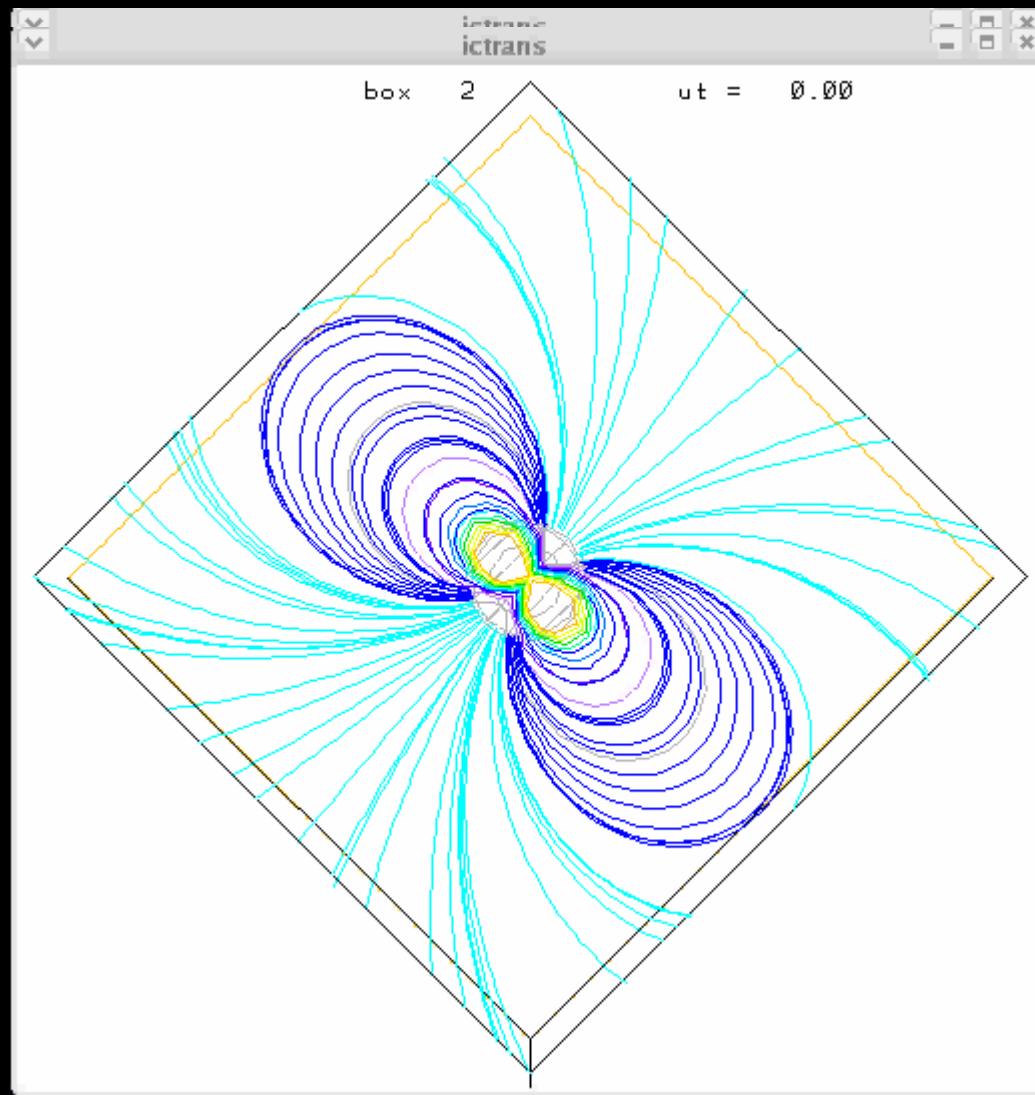
These Corrections have increasing importance for Plasma Magnet as the ion skin depth approaches scale size of the antenna

Simulation System:

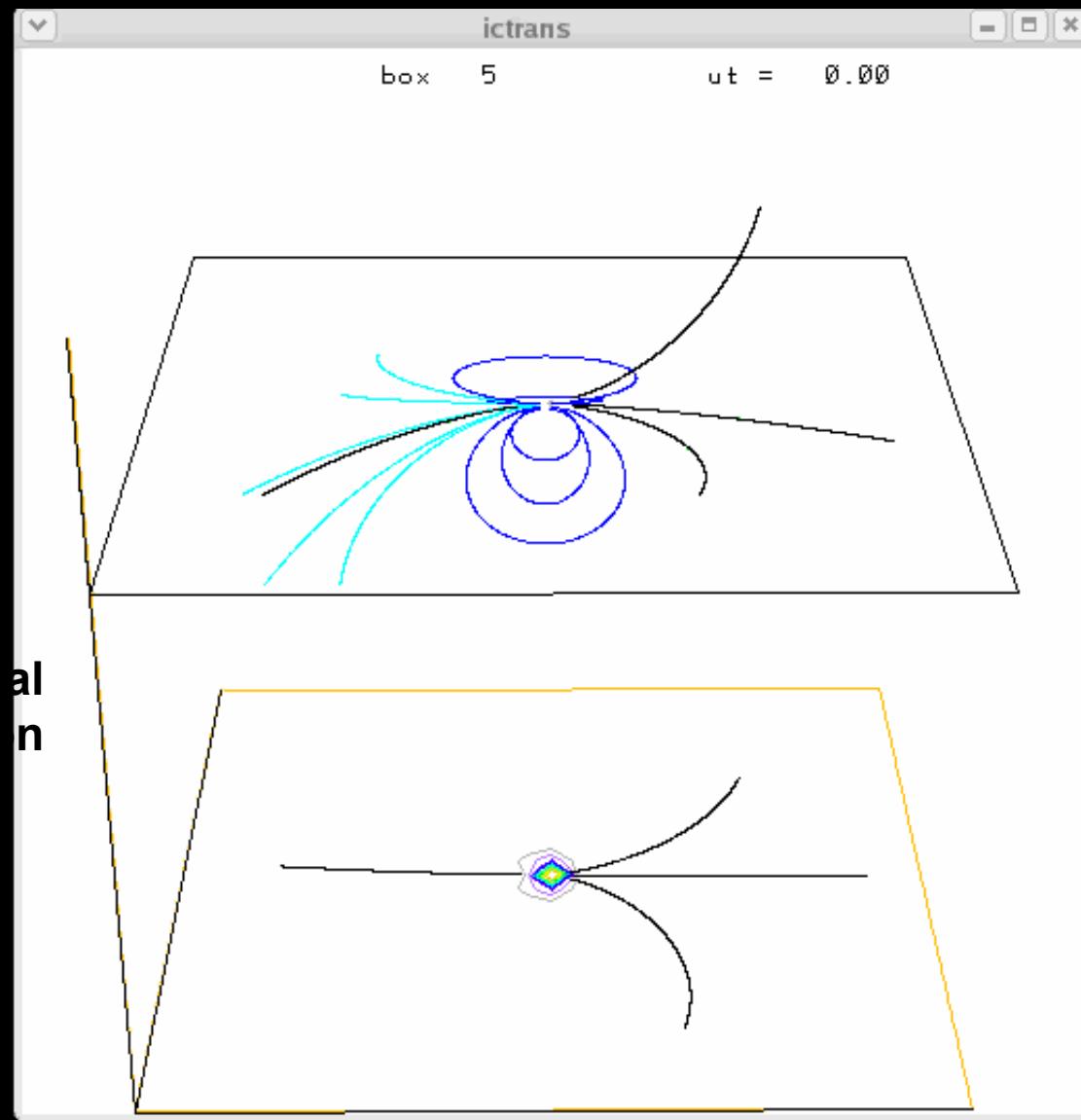
2 cm resolution out to > 5 m



Close up of the Instantaneous Rotating Magnetic Fields



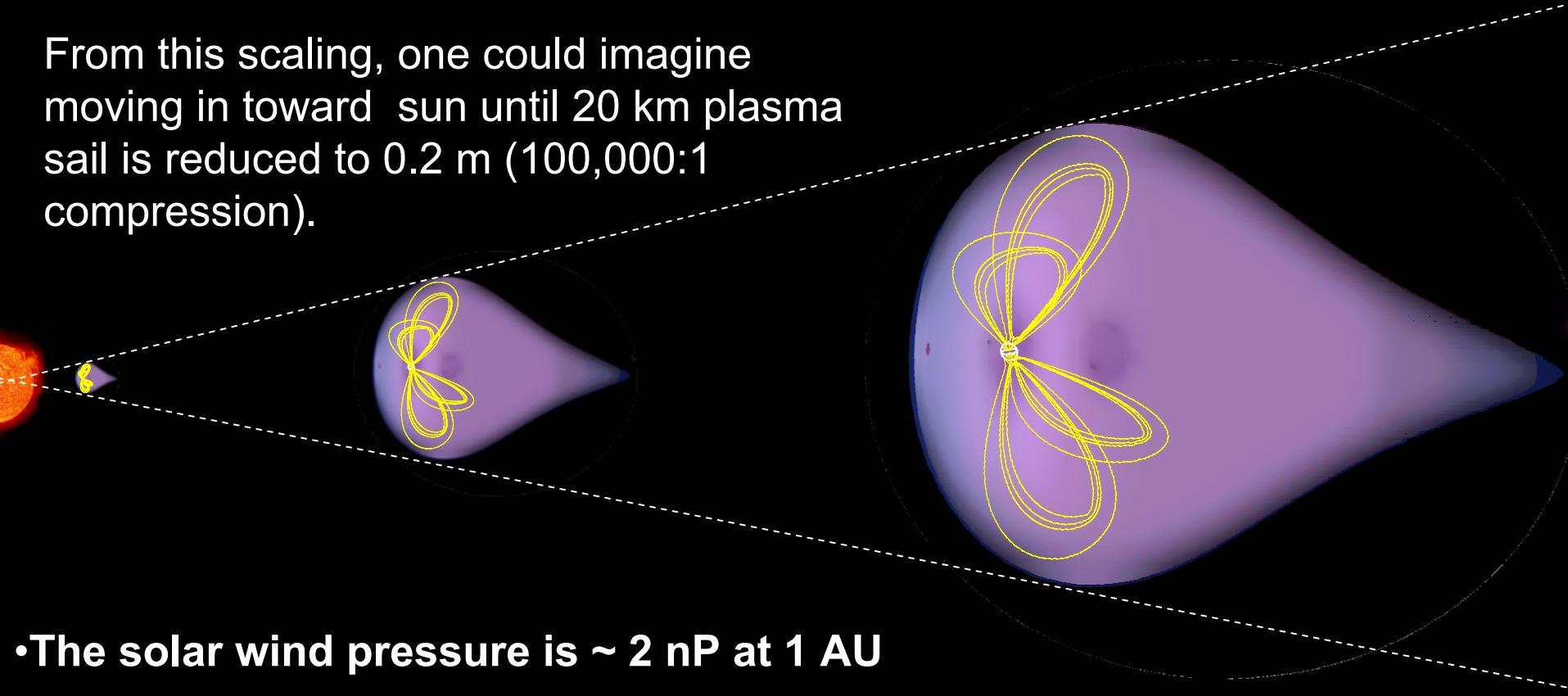
Distant Instantaneous Rotating Magnetic Fields



Plasma Magnetic Sail Size Scales with Ambient Solar Wind Pressure

(constant force sail)

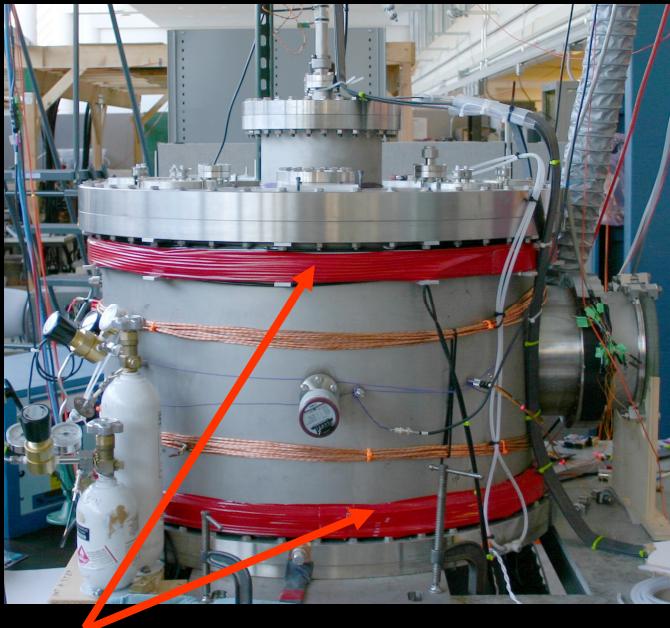
From this scaling, one could imagine moving in toward sun until 20 km plasma sail is reduced to 0.2 m (100,000:1 compression).



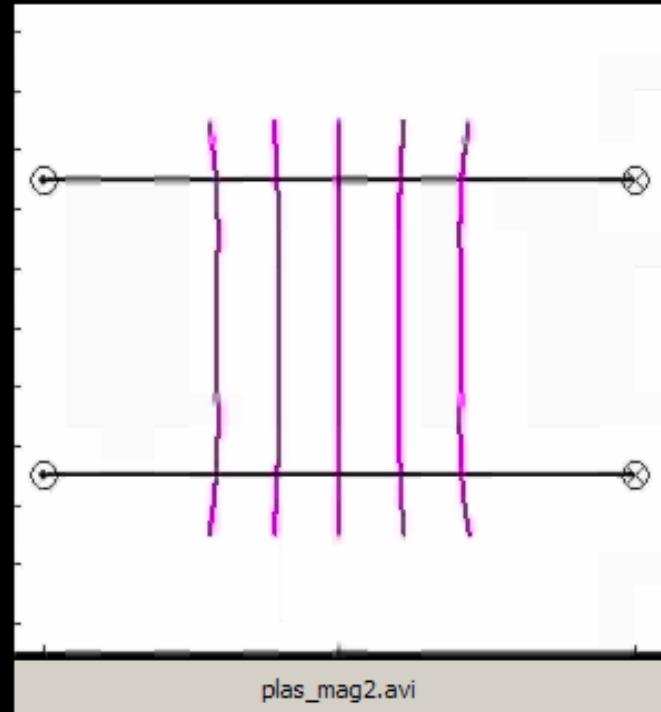
- The solar wind pressure is $\sim 2 \text{ nPa}$ at 1 AU
- The required pressure to compress down to the laboratory size is thus: $(10^5)^2 \times 2 \times 10^{-9}$ or $\sim 20 \text{ Pa}$.
- Radial magnetic pressure from a 100 G magnetic field $\sim 40 \text{ Pa}$

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)

$$T_{eV} = 6 \text{ eV}, n = 7 \times 10^{18} \text{ m}^{-3}, J = 70 \text{ kAmp/m}^2, B = 20 \text{ G}$$

$$\beta \approx 4.2 \text{ (420\%)}$$

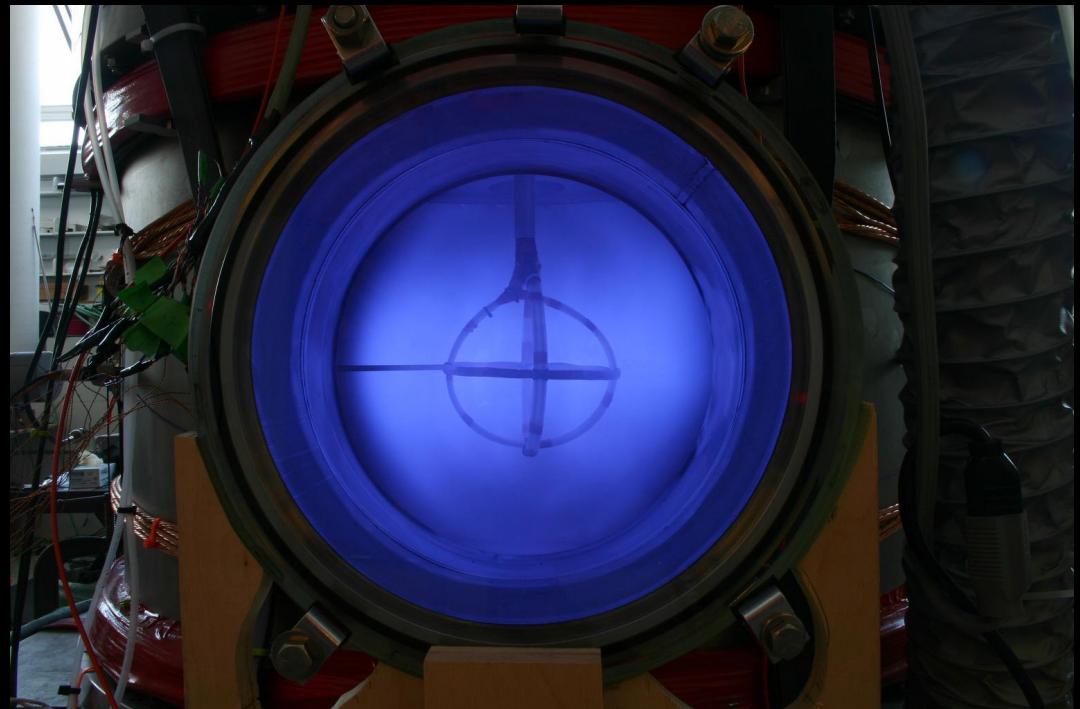
$$\nu_{ei} \approx 10 \text{ MHz}$$

$$\omega_{ce} \approx 350 \text{ MHz}$$

$$\nu_{ei} \ll \omega_{ce}$$

$$\omega_{ci} \approx 5 \text{ kHz}$$

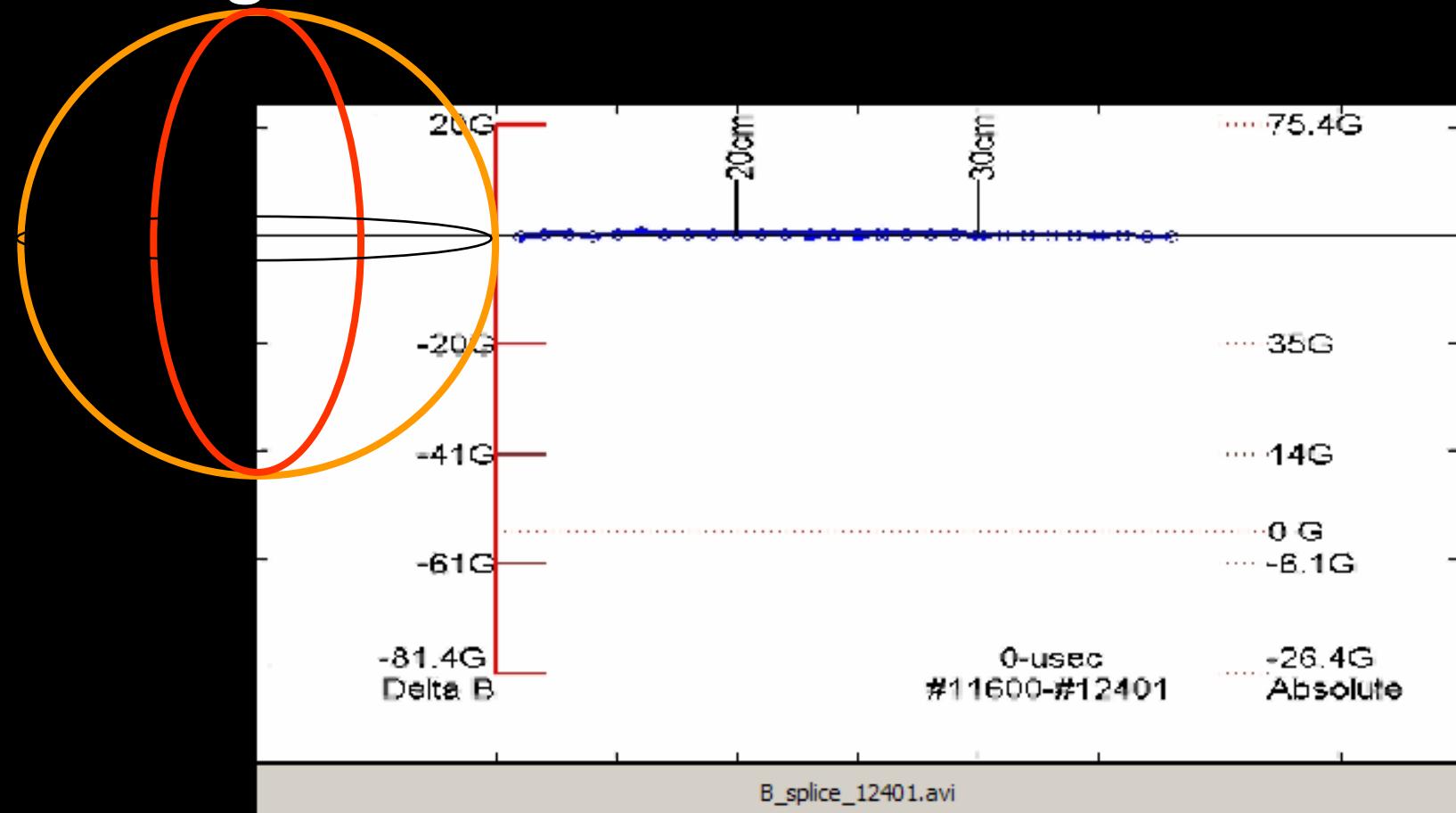
$$\omega_{ci} \ll \omega_{RMF} \ll \omega_{ce}$$



→ Operating in the RMF regime

$R = 20 \text{ cm}, 4 \text{ Pa (33 G)}$ → ~2 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 Alfvén speed

Particle Confinement in the Plasma Magnet

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

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

For lab PM (a=0.1 m, T_e ~ 6 eV) τ_N ~ 300 μsec

Assume a density fall-off of 1/r³ (not critical but less than free-streaming 1/r²):

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

$$N \sim 4\pi a^3 n_0 \ln \left(\frac{R_{MP}}{a} \right) \quad \tau_N \sim \frac{2\mu_0}{3\eta_{\perp}\beta} \ln \left(\frac{R_{MP}}{a} \right) R_{MP}^2$$

At high β (~1) and Te ~ 20 eV and for antenna radius a = 100 m with sufficient current (density n_a ~ 10¹⁶ m⁻³) to inflate to a R_{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 $1/r$ $\Rightarrow B_0 R_0 = B_{MP} R_{MP}$

$$E_B \sim \int_{R_0}^{R_{MP}} \frac{B(r)^2}{2\mu_0} \cdot dVol = \int_{R_0}^{R_{MP}} \frac{B_0^2 R_0^2}{2\mu_0 r^2} \cdot 4\pi r^2 dr = \frac{\pi}{2\mu_0} B_0^2 R_0^2 R_{MP}$$
$$= \frac{\pi}{2\mu_0} B_{MP}^2 R_{MP}^3$$

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 $\sim 1 \text{ MJ}$)

\uparrow
**80 G in lab
experiment**

*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

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

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

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

$$B_{MP} = 50 \text{ nT}$$

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

$$R_{MP} = 30 \text{ km}$$

$$P_{sw} = C_D v_{sw} \frac{\pi}{2\mu_0} C_{BR}^2 \sim 6.3 \text{ MW}$$

Drag coef. ~ 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:

$$P_\Omega = 9 \times 10^6 B_0^2 R_A^3 = 9 \times 10^6 C_{BR}^2 R_A \Rightarrow$$

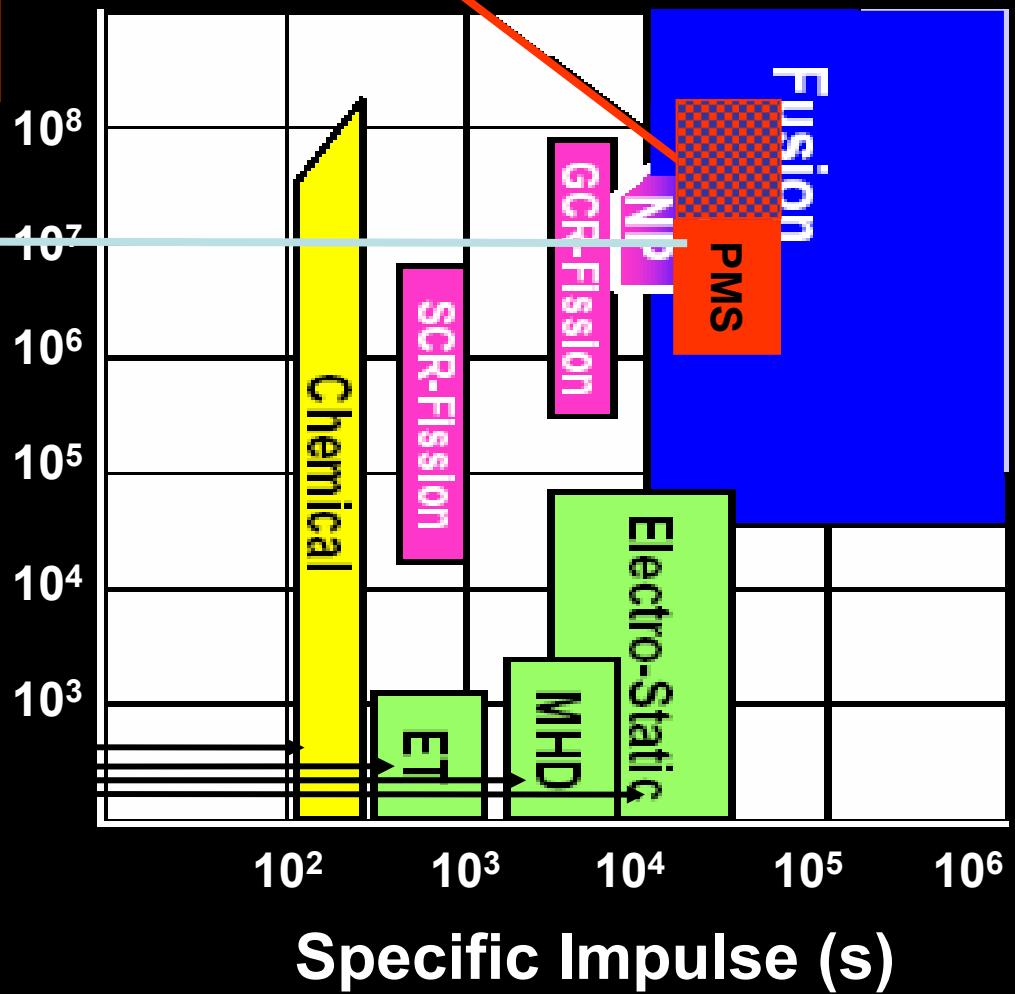
$$P_{sw} = 3.1 \times 10^5 \frac{P_\Omega}{R_A}$$

Comparison of Propulsion Systems

A Plasma Magnetic Sail (PMS) scales in principle to even higher powers depending on RMF power scaling

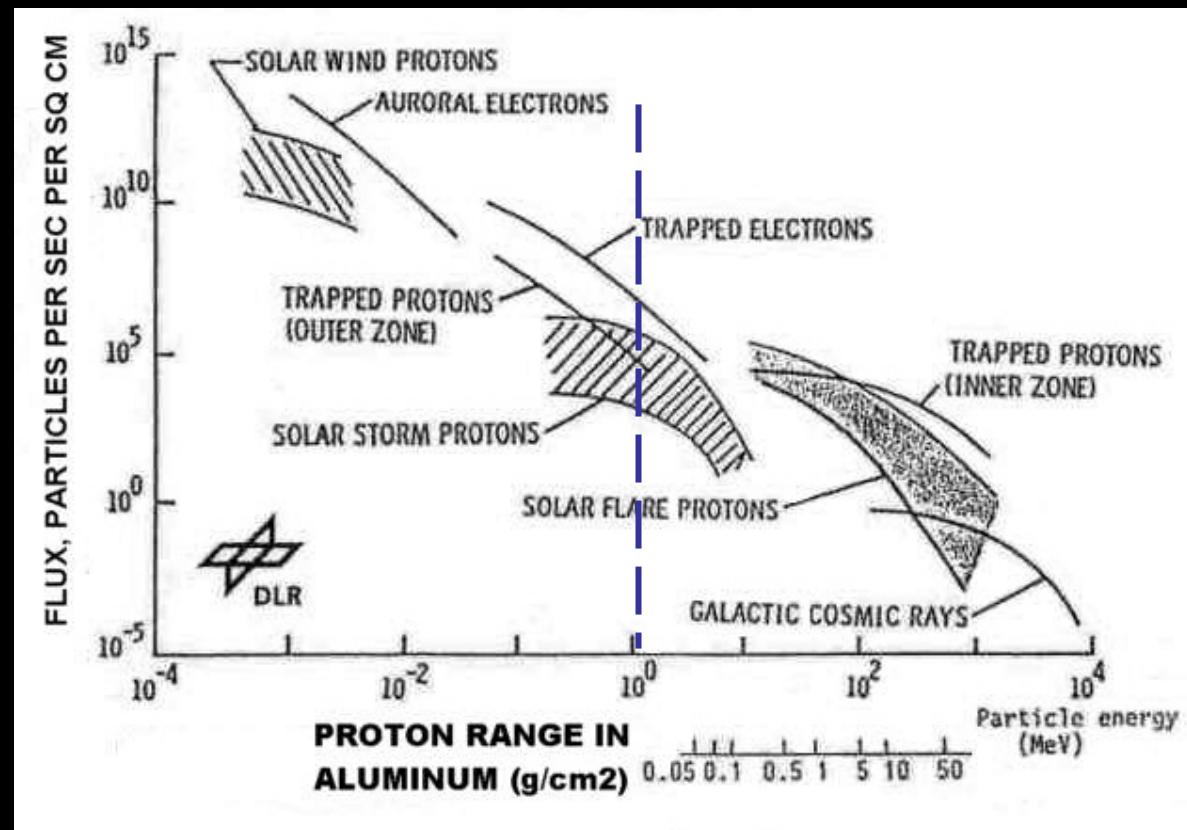
Power and exhaust velocity sufficient for rapid manned outer planetary missions

Current propulsion systems



Space Radiation Environment

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



--- aluminum skin of a spacecraft $\sim 1 \text{ gm}/\text{cm}^2$

Requirements for Radiation Shielding with a Plasma Magnet

For deflection of GeV proton one requires:

$$B_r = 2B_0 \frac{a}{r} j_l(\lambda r) \cos \theta$$

$$B_{CT} = \begin{aligned} B_\theta &= -B_0 \frac{a}{r} \frac{\partial}{\partial r} (r j_l(\lambda r)) \sin \theta \\ B_\phi &= \lambda a B_0 j_l(\lambda r) \sin \theta \end{aligned} \quad B_0 a \sim 1 \text{ T-m}$$

$$\int_0^{R_M=a} \mathbf{B} \cdot d\mathbf{s} \approx \int_0^a B_{CT} dr \sim 1 \text{ T-m}$$

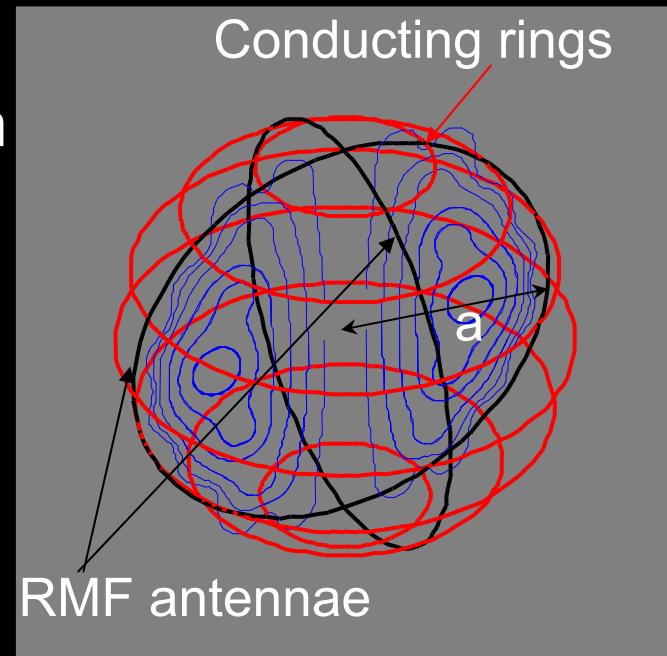
From previous scaling analysis:

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

$$P_{RMF} = \int \eta j_\theta^2 \cdot dVol \cong \frac{4\pi\eta}{\mu_0^2} B_a^2 a = \frac{40}{a} \text{ (MW)}$$

For $a \sim 100 \text{ m}$:

$$\Rightarrow P_{RMF} = 400 \text{ kW with charging time of } 600 \text{ s}$$



Current Work on the Plasma Magnet Sail

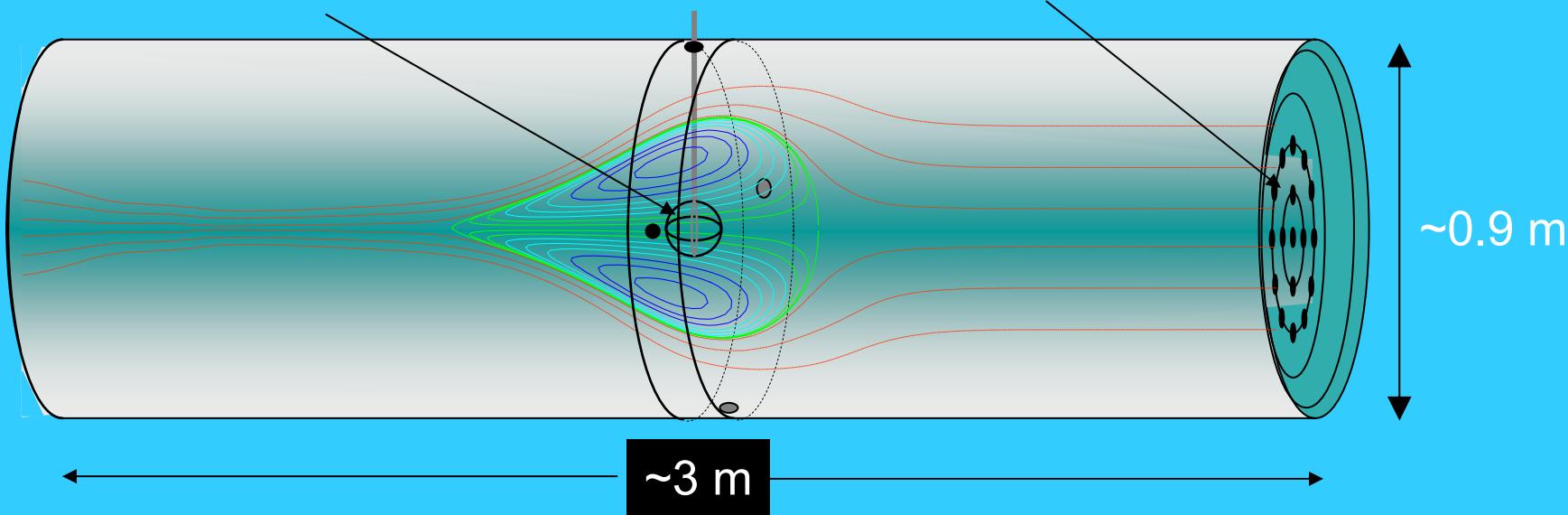
Perform the critical experiments for concept validation

- 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

Rotating Magnetic Field Antenna
(pendulum suspended)

Lab Solar Wind Source
(array of MCAS)

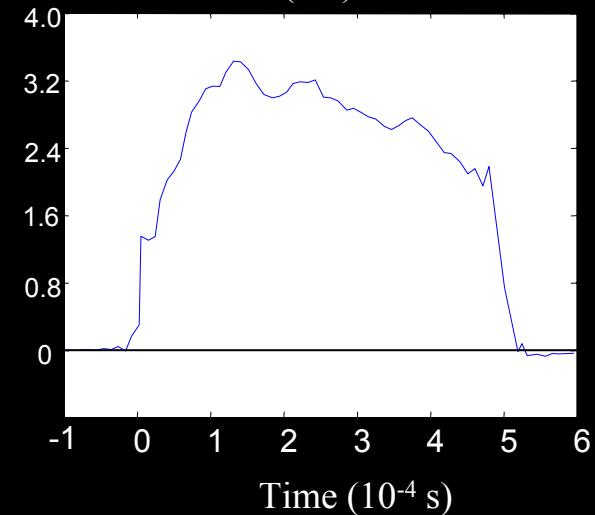
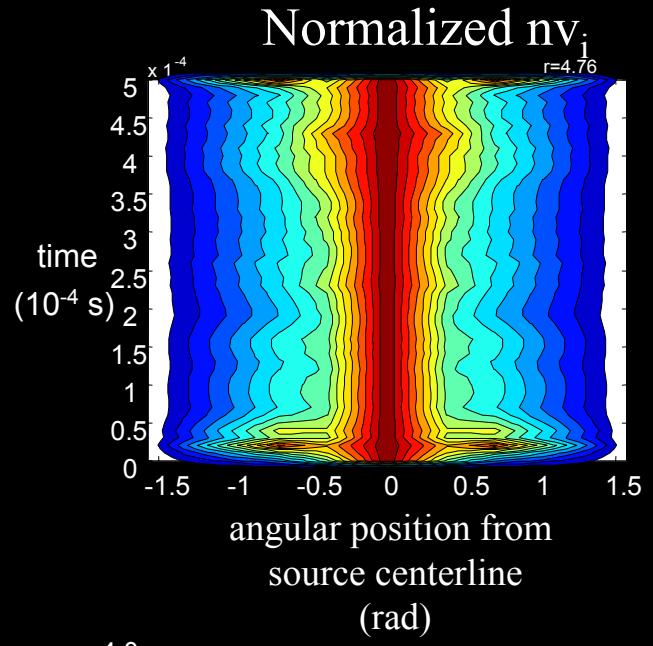
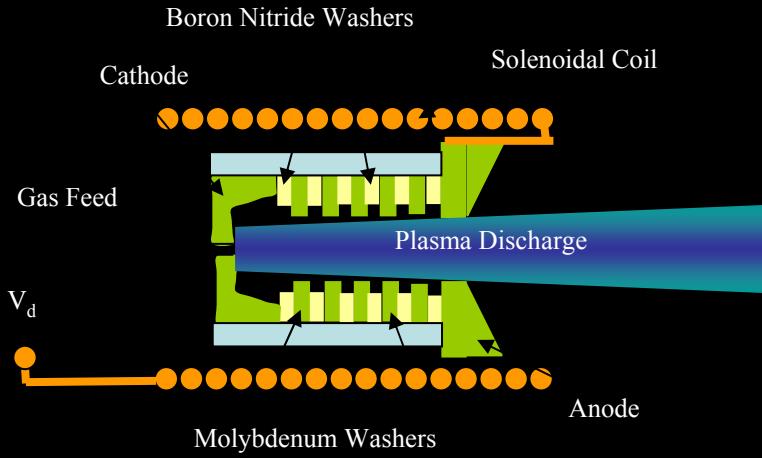


- Want to maintain plasma magnet size to observe expansion against Laboratory Solar Wind (LSW) $D_{\text{Antenna}} \sim 1/4 (0.4 \text{ m}) - 0.1 \text{ m}$
- With Constant force expansion/contraction need $\Rightarrow P_{\text{LW}} = P_{\text{SW}} = 2 \text{ MW}$
- Want ρ_i/R to scale for kinetic effects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

Plasma Wind Tunnel Under Construction



Magnetized Cascaded Arc Source

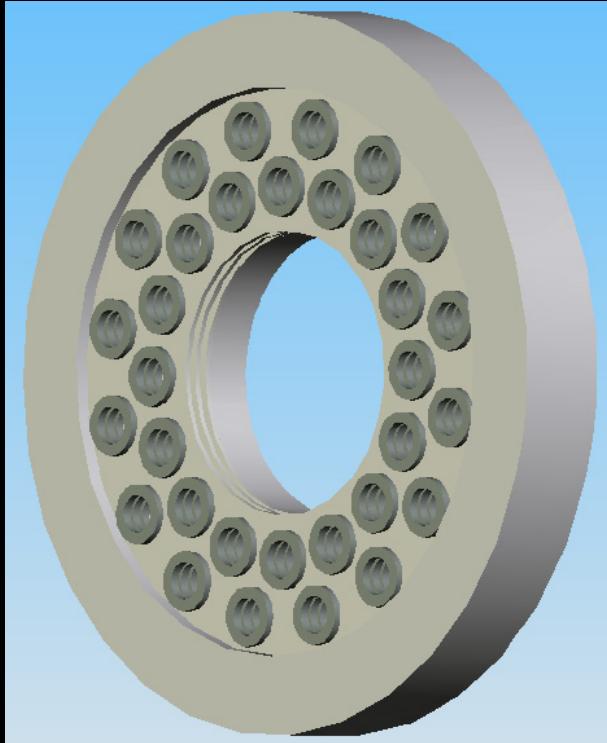


Directed force from plasma gun can be substantial.

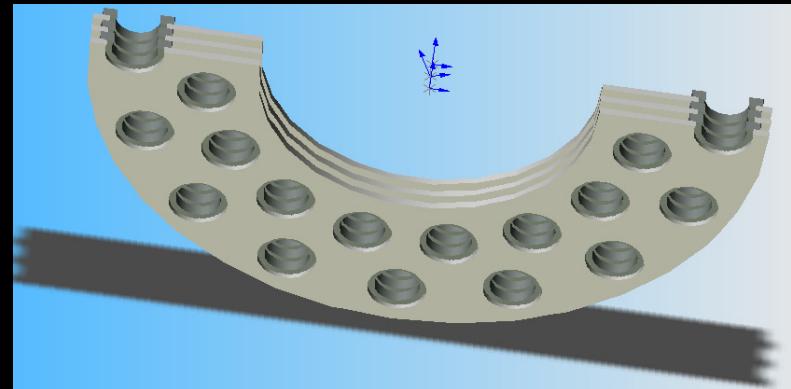
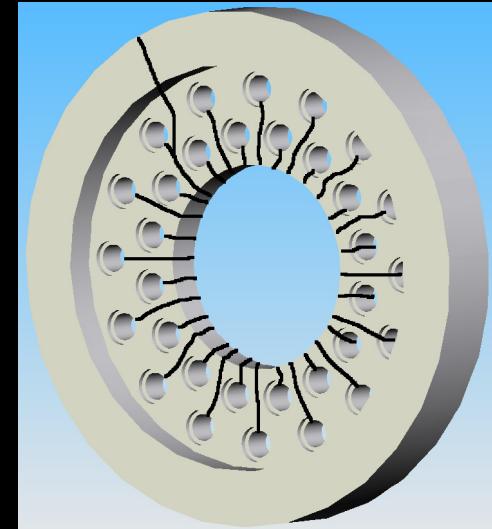
From probe measurements:
 $(I_{\text{dis}} \sim 2 \text{ kA}), v_s \sim 35 \text{ km/s (H)}$

$$F_z = \frac{dN}{dt} m_i v_s = 0.15 - 0.25 N$$

MW Plasma Source for Surrogate Solar Wind



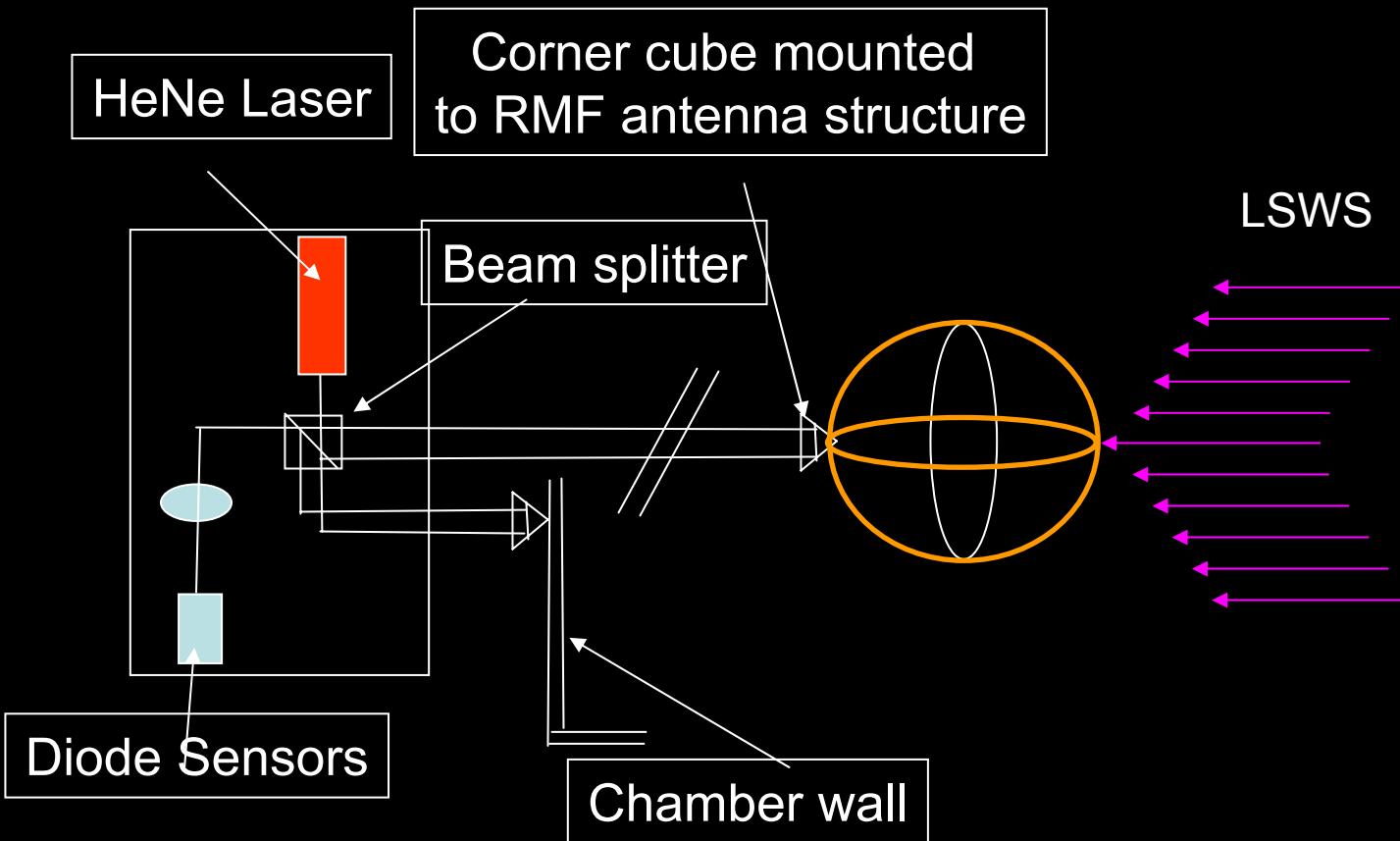
Aluminum disk
with flux slits



Final assembly (minus Macor)

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

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

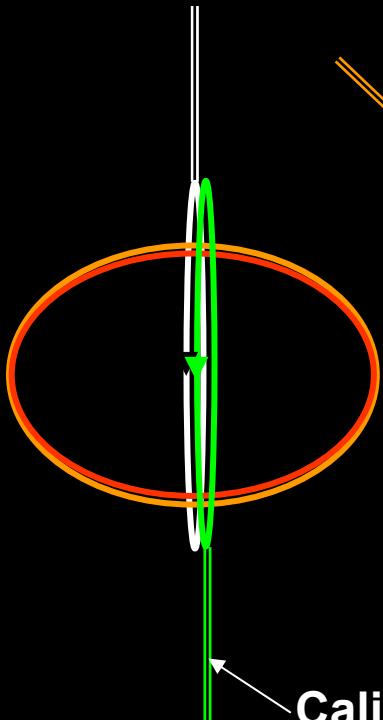
a = loop radius

d = loop separation

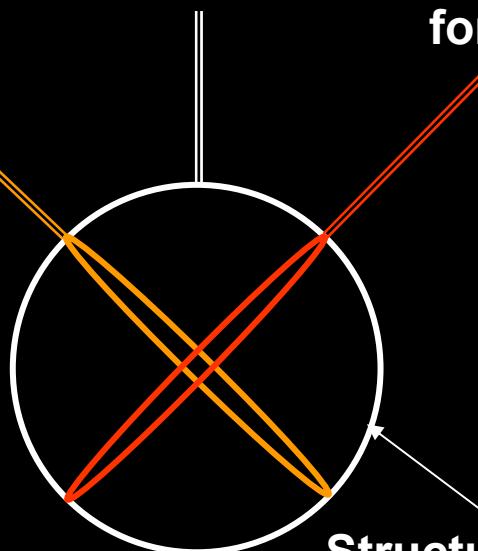
a/d ~ 20

For 1 N force,
I ~ 200 A

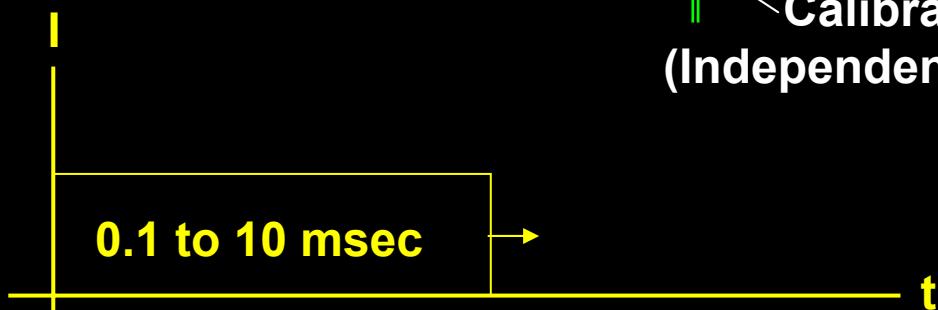
Side view



Front view



Current feed/support
for RMF loops



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 (\sim kW, \sim kJ, grams)
- If confirmed in future scaling experiments, other uses such as GCR radiation shielding become feasible