NASA Institute for Advanced Concepts

Phase I Fellows Meeting

The Plasma Magnet

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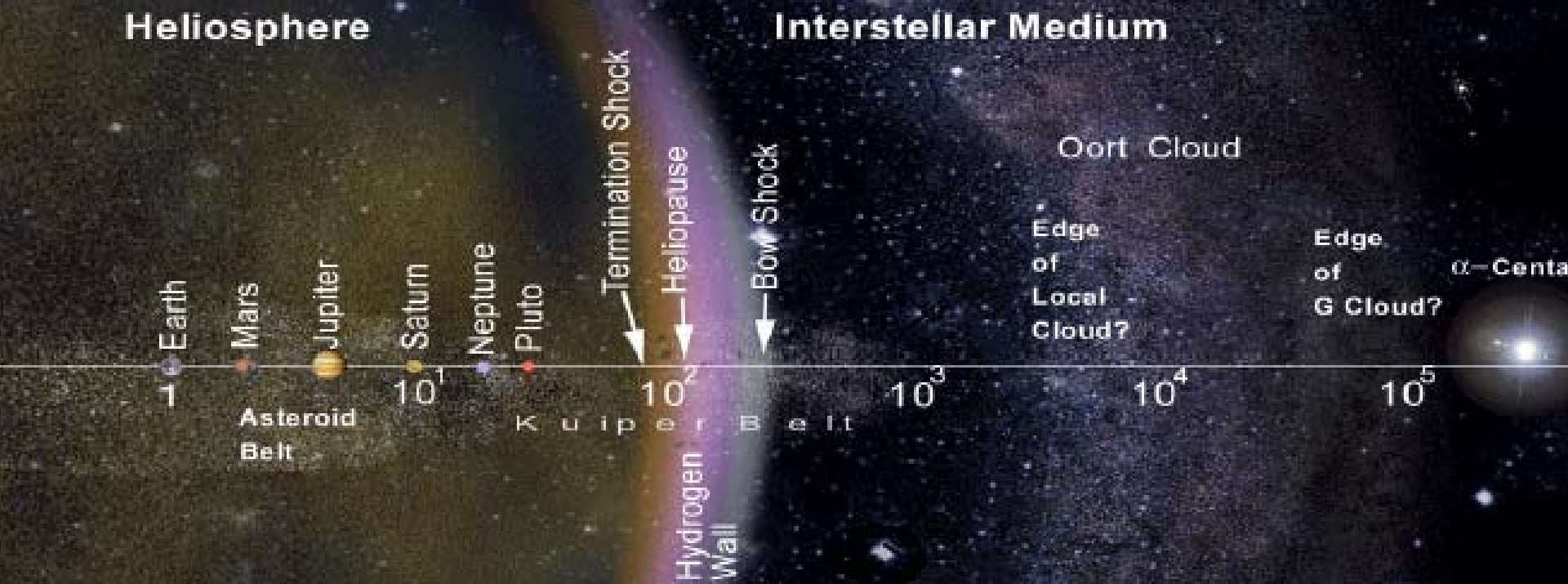
University of Washington

March 23-24, 2004

Development of the Plasma Magnet for Deep Space Exploration



John Slough, Samuel Andreason, and Louis Giersch

Research Institute for Space Exploration
University of Washington

NASA / Interstellar Probe Science & Technology Definition

The Plasma Magnet

- The singularly most important aspect is the possibility of achieving multi-Megawatt thrust power from the solar wind.

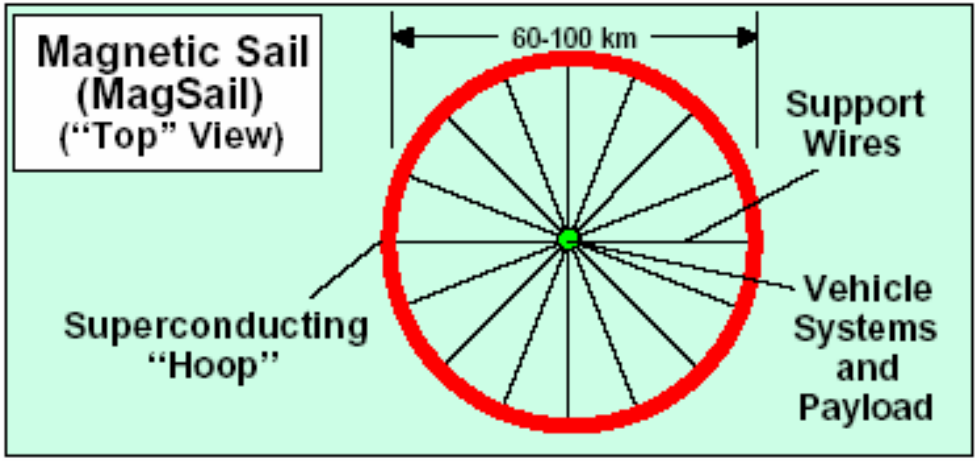
- The ultimate spacecraft speed powered by the plasma magnet is that of the solar wind (350 to 800 km/s).

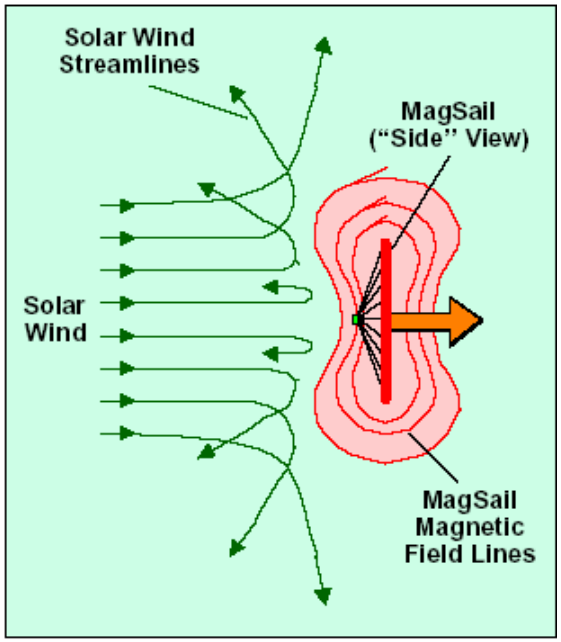
- As opposed to the solar sails, the dynamic nature of the plasma magnet provides a constant thrust regardless of distance from the sun.

- The jet power scales with the size of the magnetic bubble. A 20 kW rotating magnetic field (RMF) can produce a magnetic bubble intercepting up to 10 MW of thrust power. The effective "thruster" efficiency can be greater than 1 – and as large as $\eta \sim 500$

The Magnetic Sail

(Zubrin and Andrews,1991)

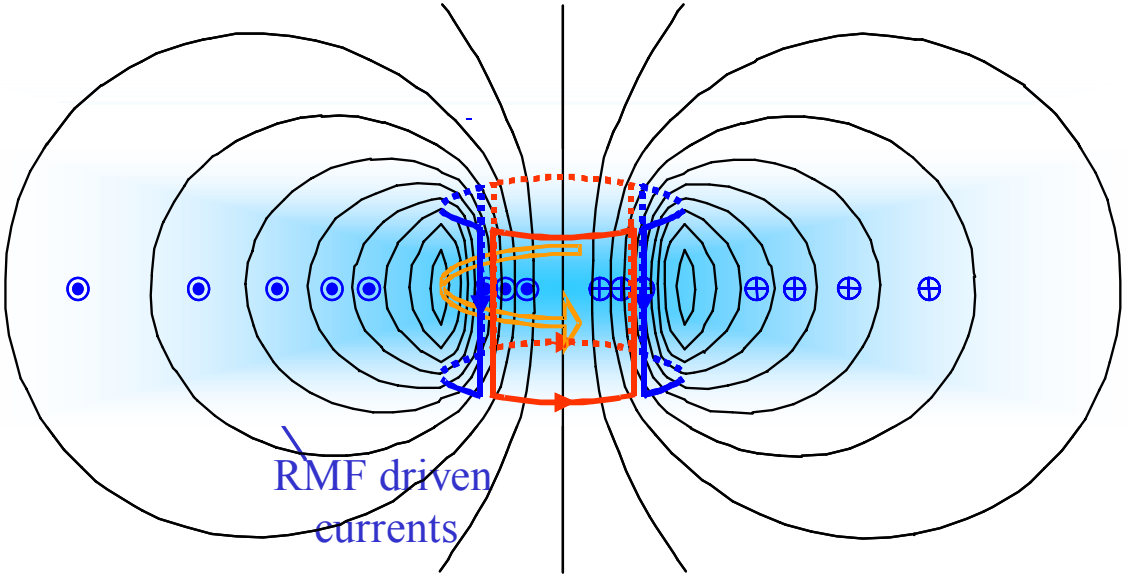




- The major difficulty in the original concept of course was the magnet mass.
- The mass problem is solved by having the coil currents conducted in a plasma rather than a superconducting coil. In this way the mass of the sail is reduced by orders of magnitude for the same thrust power.
- The question now becomes how to generate and sustain the currents

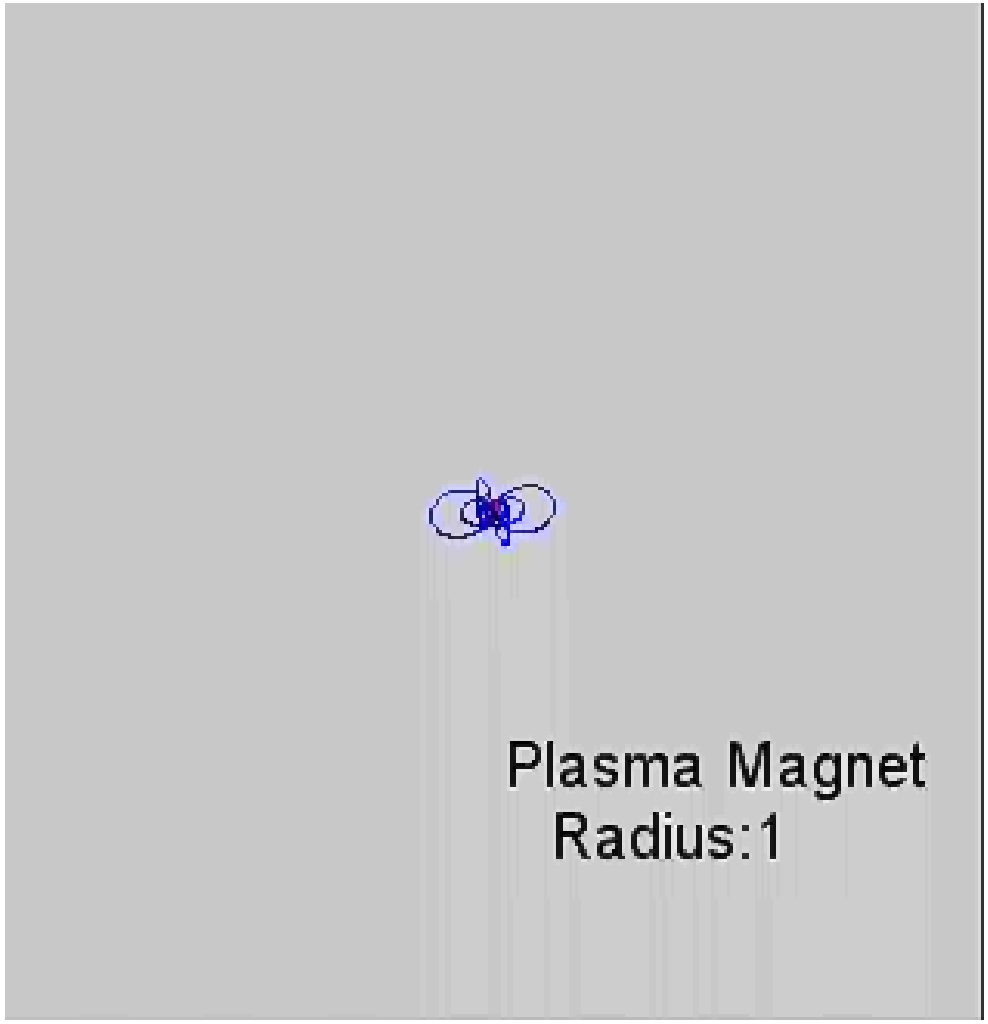
How are the plasma currents generated and sustained?

Plasma Magnet from Rotating Magnetic Fields



- No copper/superconducting magnet required
- Results from Phase I Have demonstrated generation and sustainment of high β dipole plasma equilibria with 10 kA of azimuthal plasma currents

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

Physics of RMF Current Drive

Electron equation of motion in rotating field, $\mathbf{B}_\omega$:

where, $$-\frac{e}{m}\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}\right)-\nu_{ei}\,\mathbf{v}=\omega\mathbf{v}$$

$$B_r=B_\omega\cos(\omega t),\quad B_\theta=B_\omega\sin(\omega t),\quad \mathbf{E}=E_z=\omega r B_\omega\cos(\omega t)$$

Assuming $\omega << \nu_{ei}$, one obtains the following Ohm's law:

$$\mathbf{E}=\eta\mathbf{j}+\frac{1}{ne}\mathbf{j}\times\mathbf{B}\qquad \eta=\frac{m\nu_{ei}}{ne^2}\qquad \mathbf{j}=-ne\mathbf{v}$$

The Hall term dominates when,

$$\frac{B_\omega}{ne}>>\eta\quad\Rightarrow\quad\frac{eB_\varpi}{m}\equiv\omega_{ce}>>\upsilon_{ei}$$

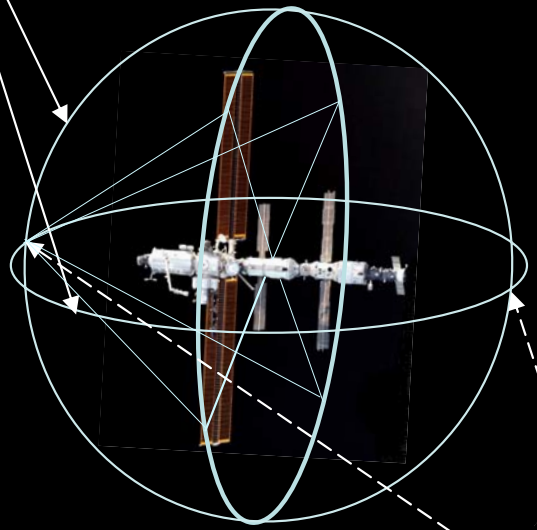
In a metal conductor the Hall term is small (large ν_{ei}), and one has the rotating field penetrating only the classical skin depth $\delta = (2\eta/\mu\omega)^{1/2}$.

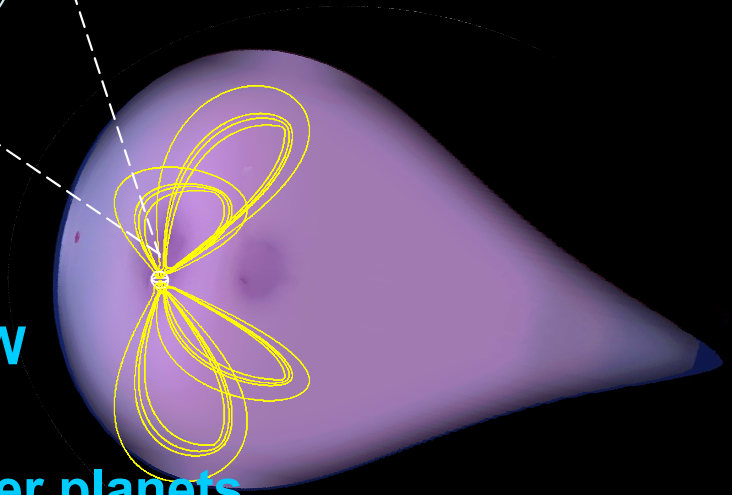
The θ component: $$E_\theta=\eta j_\theta-\frac{1}{ne}\left(u_r B_z-\langle j_z B_r\rangle\right)$$

The Hall term has a pondermotive component, the $\langle j_z B_r\rangle$ term acting in the θ direction. It is the steady component of this electric field that drives the magnet current and provides for a steadily increasing magnet flux

Plasma Magnet: Sailing the Solar Wind

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 ≥ 10 km)





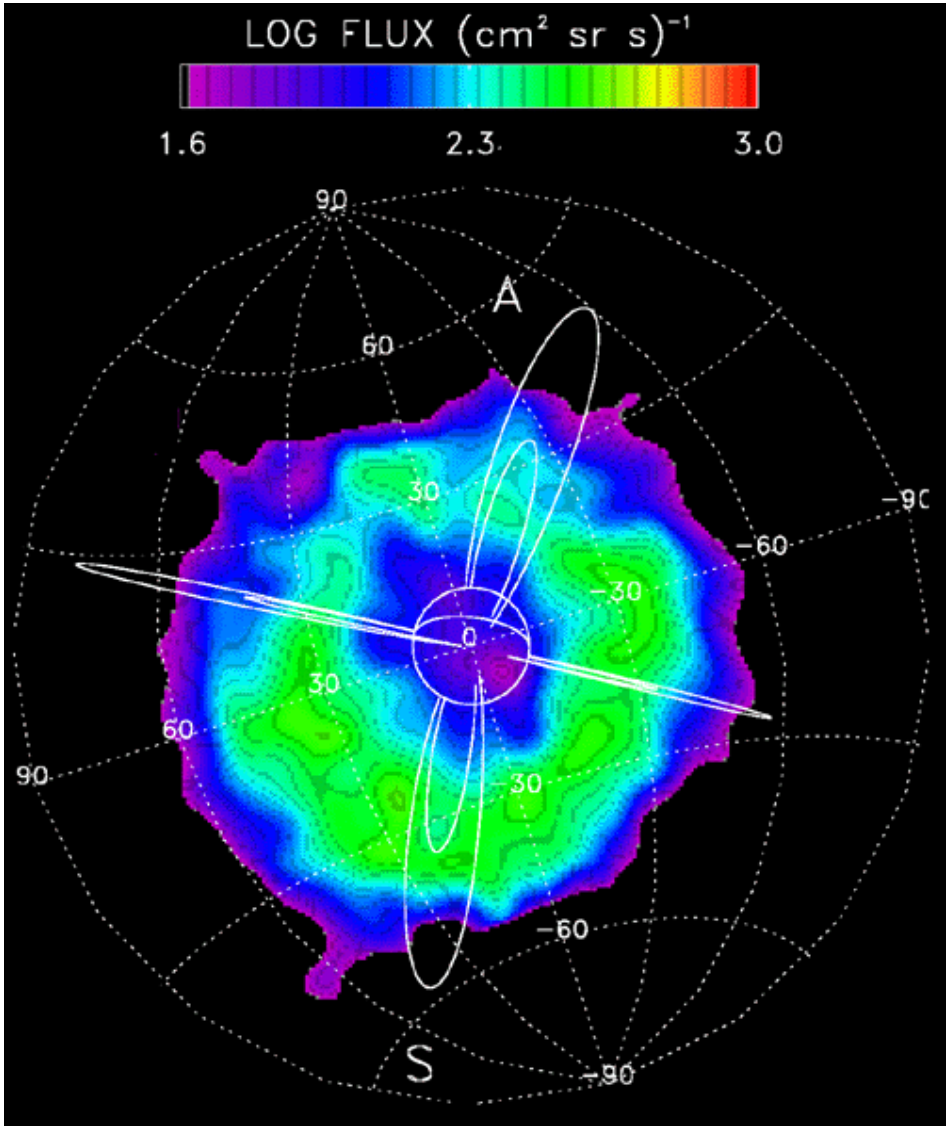
plications:

- ulti-MW thruster leveraged from multi-KW RF power
- agneto-braking in magnetosphere of outer planets
- ectrical power generation from back emf on RF field coils from solar plasma flow (solar windmill)
- agnetic shielding of spacecraft from high energy solar particles

Terrestrial Current Ring

Currents driven by the RMF find an analogous representation in the ring currents formed when the magnetosphere is compressed by the solar wind.

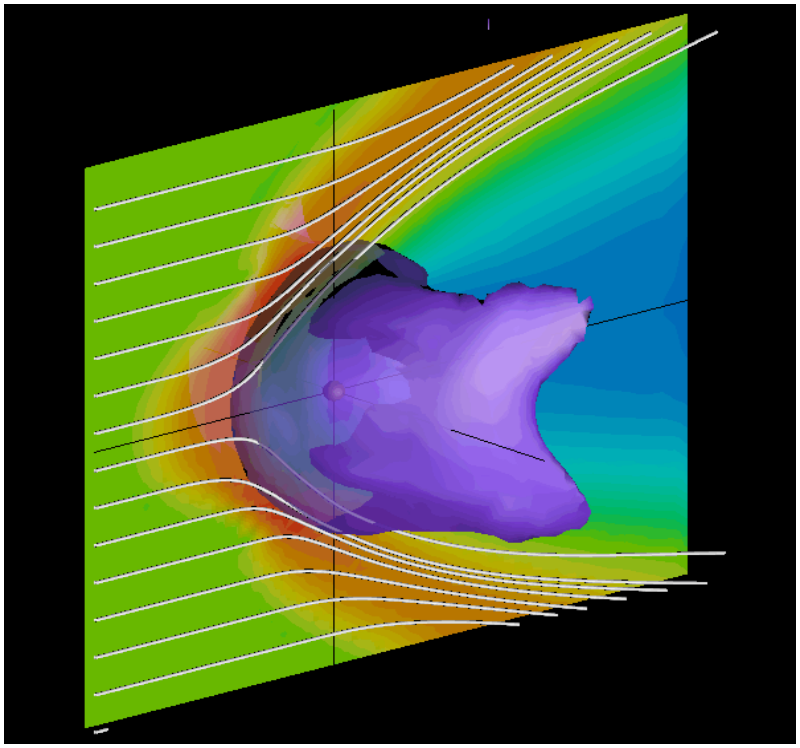
The process of course is reversed for the plasma magnet where the driven ring current acts to expand the magnetic bubble pushing off the solar wind.



FUNDAMENTALS OF THE PLASMA SAIL CONCEPT:

- Once inflated, the interaction of the plasma magnet with the solar wind should be similar to that of the planetary magnetosphere or plasma sail.
- For strong interaction with the solar wind the magnetic bubble must be on the order of the solar wind proton Larmor radius (~ 100 km) and the ion inertial length (~70 km).
- Sufficiently large initial plasma Bubble assures the both inflation and strong interaction (plasma magnet)

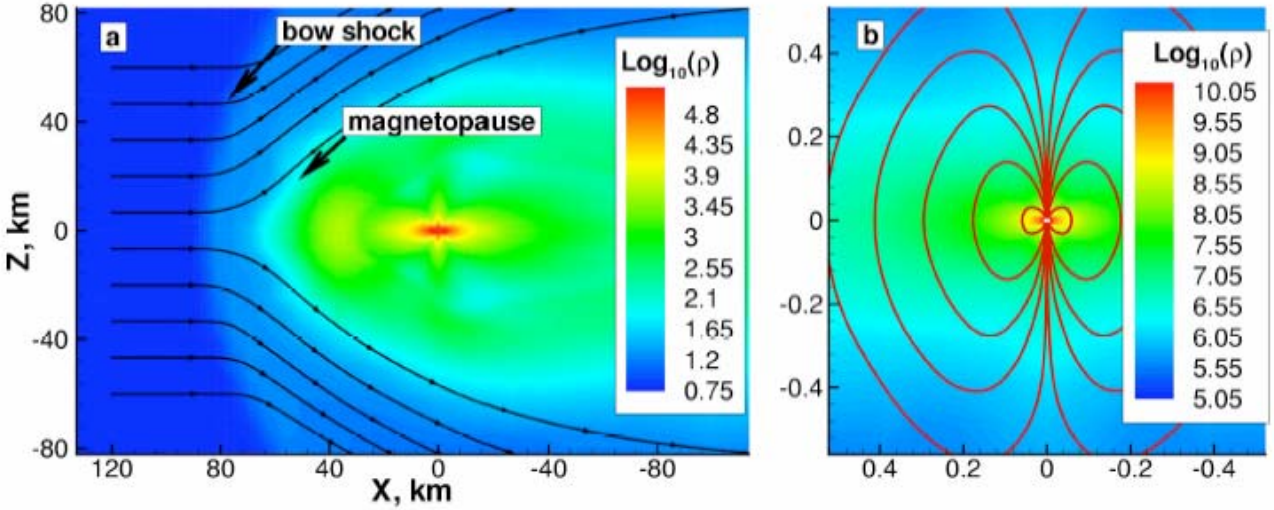
Mini-Magnetospheric Plasma Propulsion



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

UNDAMENTALS OF THE 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

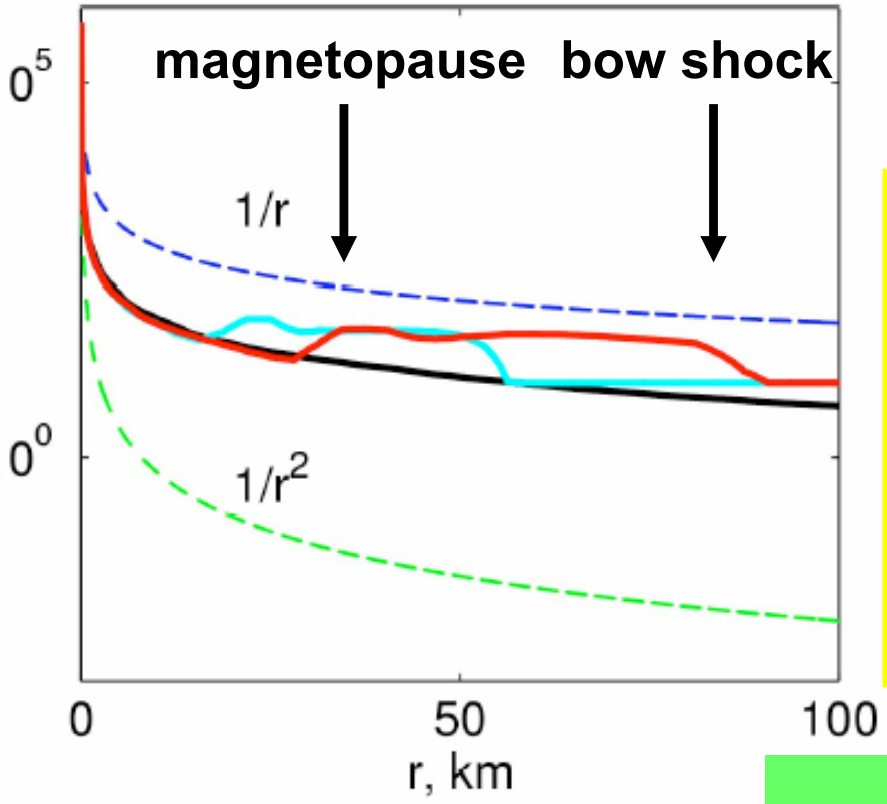
From G. Khazanov et al. AIAA JPC 2003

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

20 km radius barrier receives a force of 4 Newtons

Total thrust power ~ 2 MW

The Magnetic Field Fall-off in the Sub-solar Direction for a 40 km Plasma Sail



From G. Khazanov et al.
AIAA JPC 2003

A dipole field of B_{z0} = 6 G (6x10^5 nT) at 10 m was assumed

Size of plasma sail scales with magnitude of dipole field. By employin the RMF, the size of the plasma sail is limited only by the power to overcome dissipation In the plasma:

$$\Rightarrow \quad P_{sw} \sim \frac{\mu_0}{8\eta} v_{sw} R_0^2 P_{RMF} = 6x10^3 R_0 P_{RMF}$$

Red line - MHD simulation with solar wind

Black line – without solar wind

Light Blue line - solar wind with increased dynamic pressure.

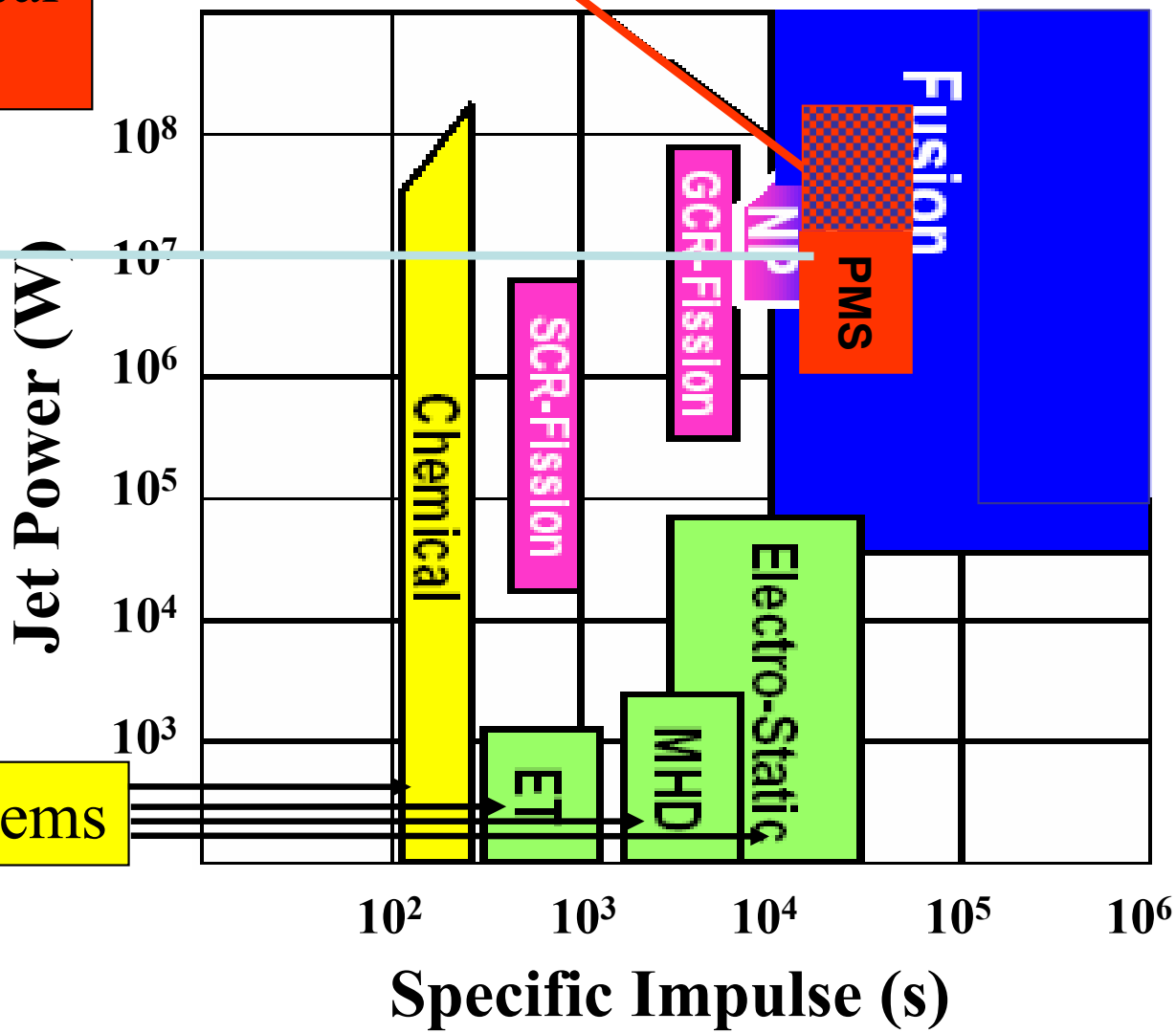
Thin dashed lines show 1/r and 1/r² dependences for comparison.

A Plasma Magnetic Sail (PMS) could scale in principle to even higher powers with small nuclear source

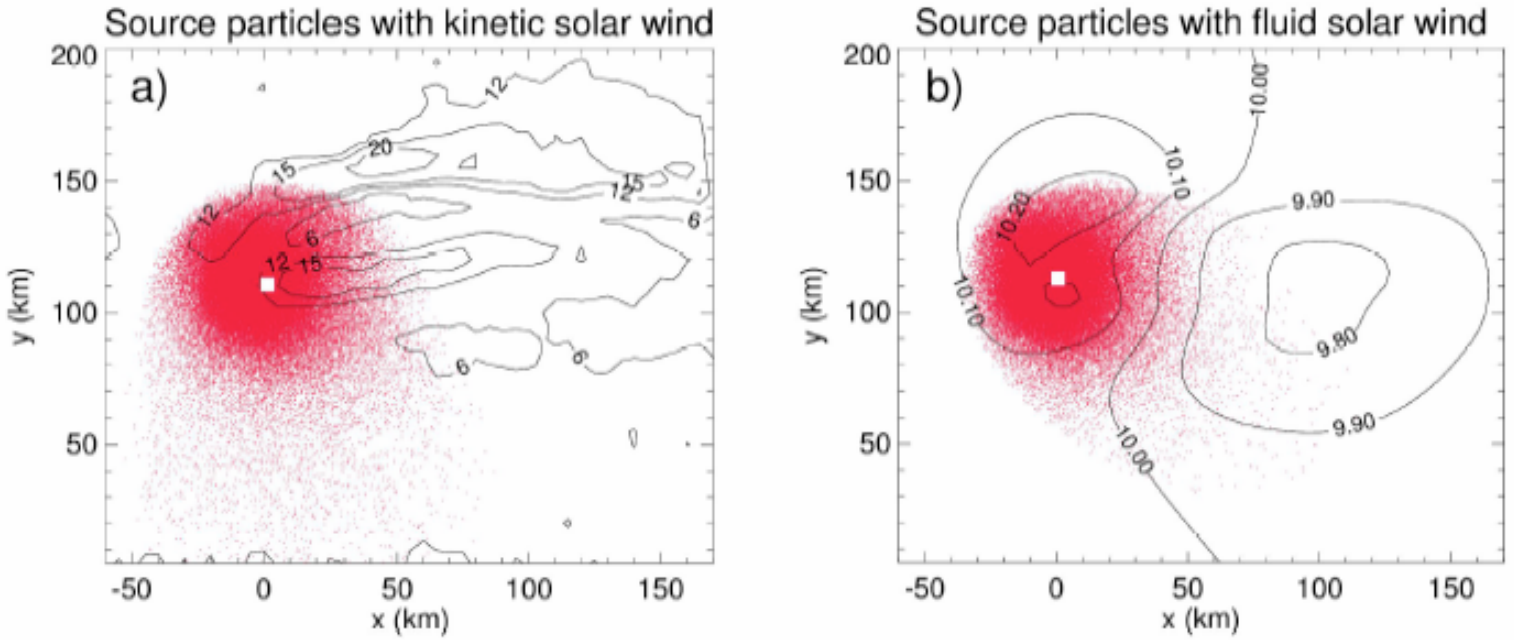
Power and exhaust velocity sufficient for rapid manned outer planetary missions

Current propulsion systems

Comparison of Propulsion Systems



Comparison of Kinetic and Fluid Treatment of the Solar Wind in the Plasma Sail Interaction



$F_x \sim 3.4$ N

$F_y \sim 1.4$ N

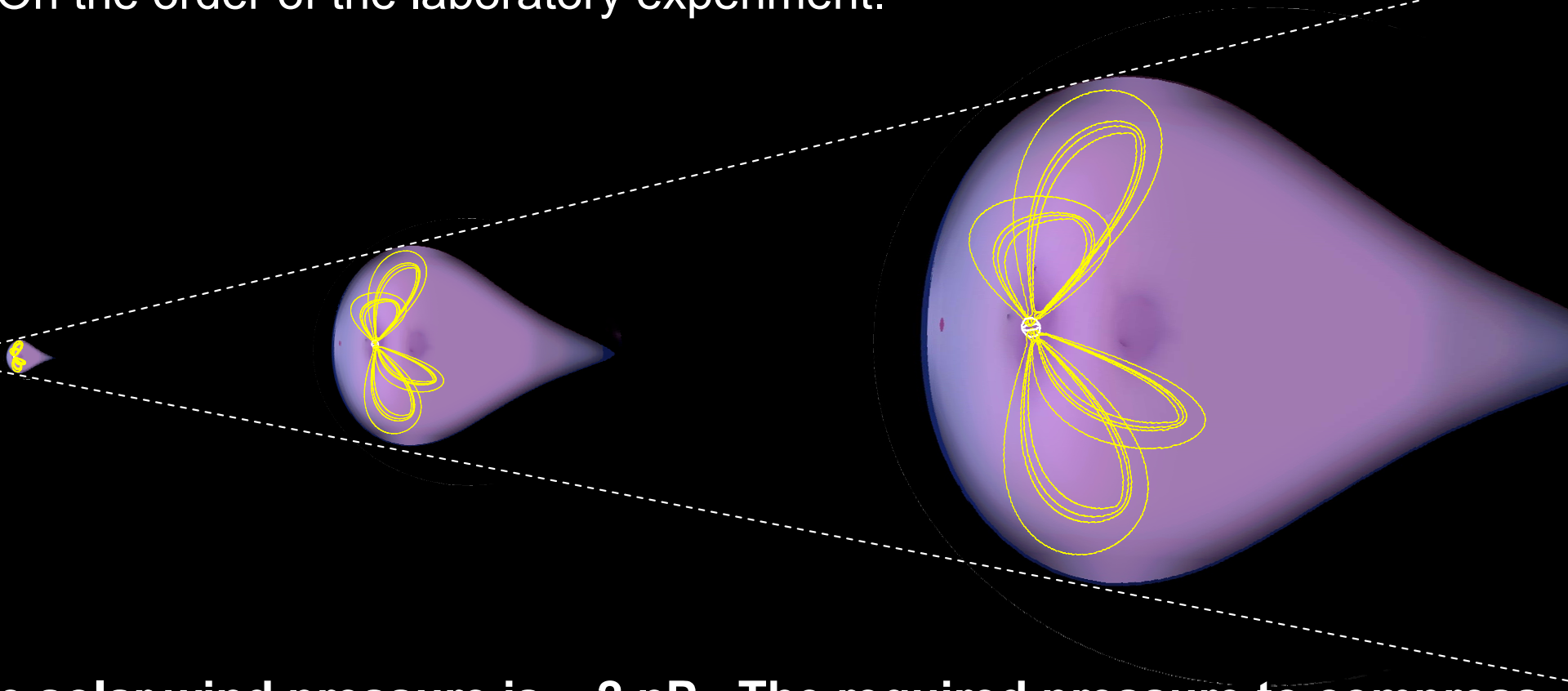
Contours show the density of the solar wind particles
Source particles are indicated in red.

- 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

With magnetic bubble size determined by ambient solar wind pressure, for
on plasma sail remains constant as spacecraft moves outward (or inward).

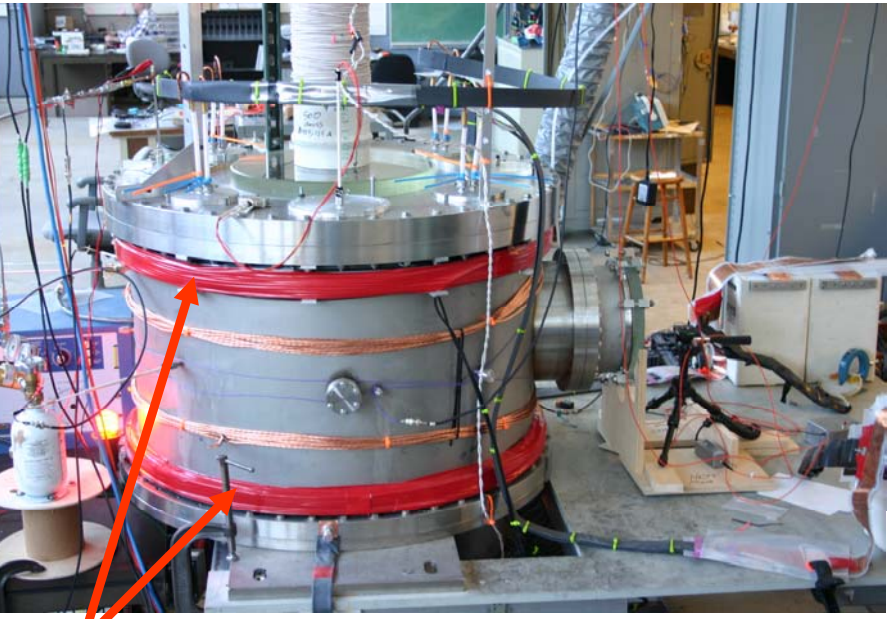
From this scaling, one could imagine moving in toward sun until 20 km
plasma sail is reduced to 0.2 m (100,000:1). The scale of the sail is now
On the order of the laboratory experiment.



e solar wind pressure is ~ 2 nP. The required pressure to compress
own to the laboratory size is thus $(10^5)^2 \times 2x10^{-9}$ or ~ 20 Pascals.
he radial magnetic pressure from a 100 G magnetic field is ~ 40 Pasca

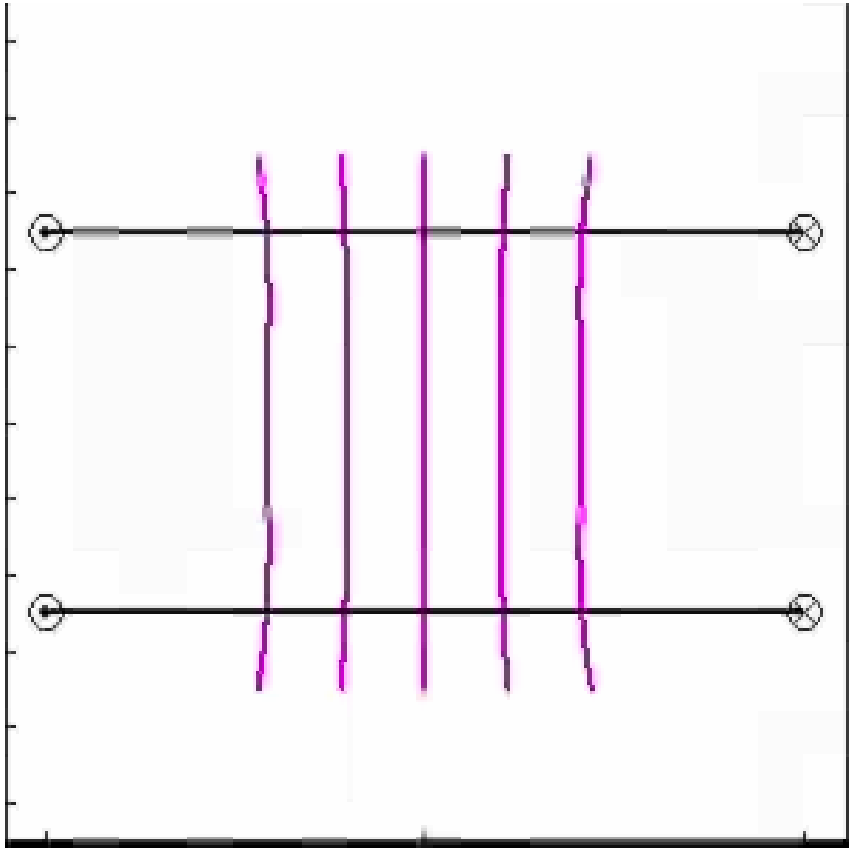
Phase I Feasibility Experiments at the University of Washington

With the external magnetic field parallel to the polar axis, a radially inward pressure will oppose the plasma expansion, much like the solar wind will do in space. The plasma magnet will thus remain compressed at the meter scale from the kilometer scale.

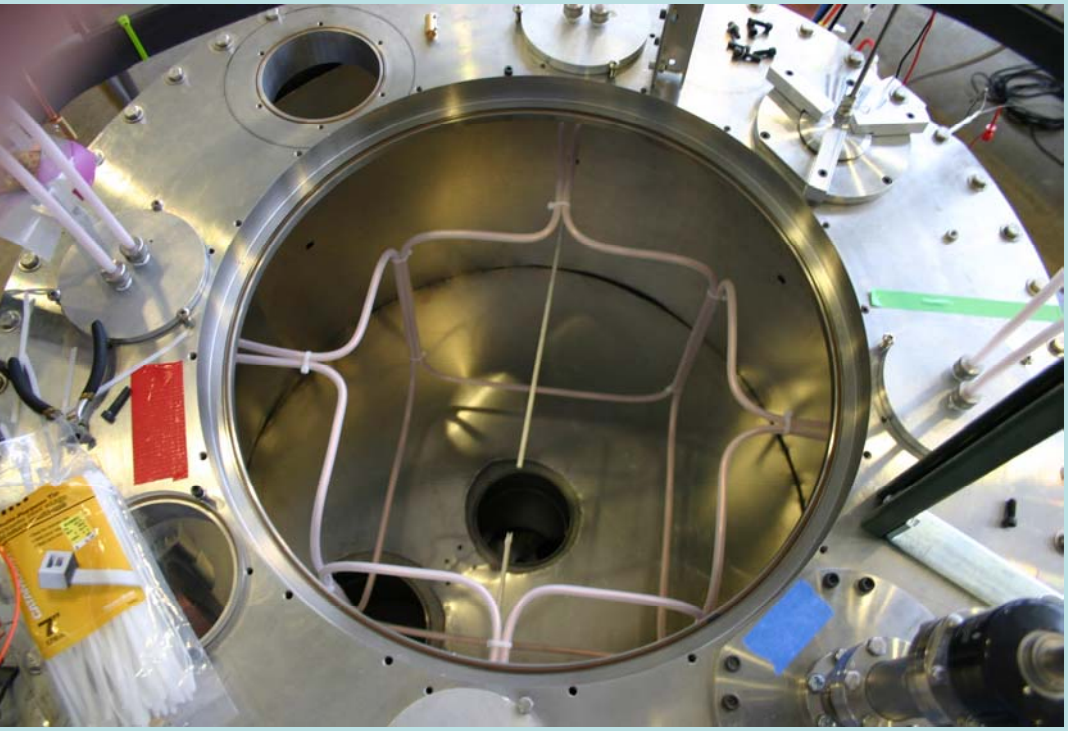


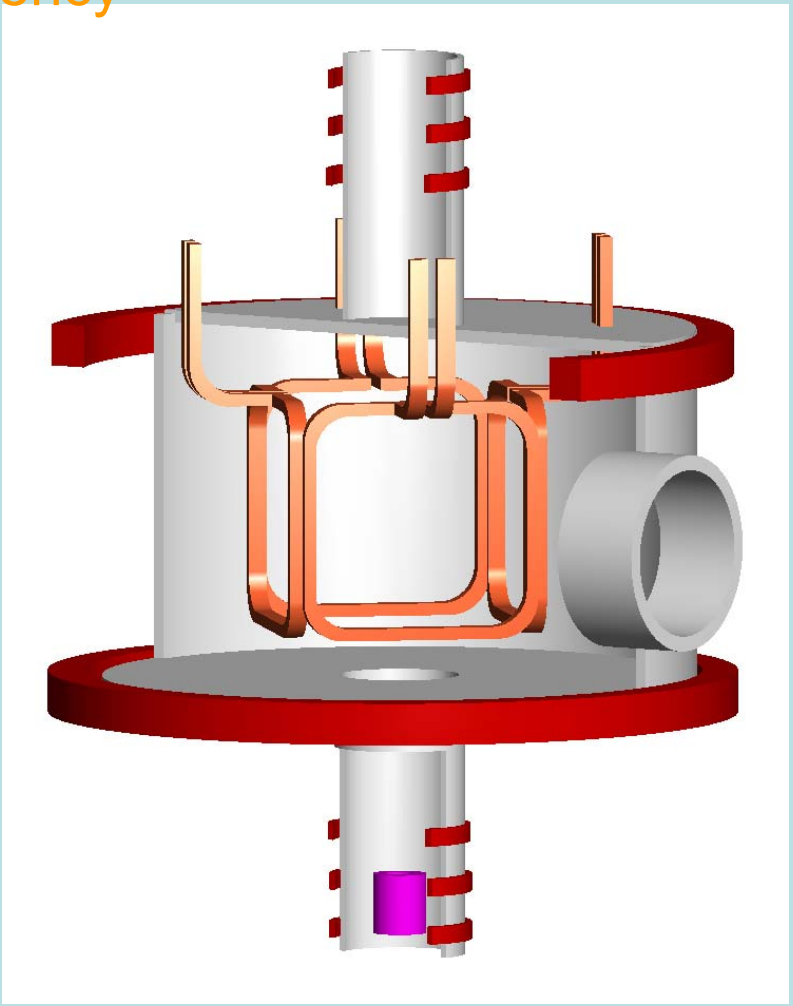
Helmholtz pair produces external magnetic field

(Solar wind surrogate)



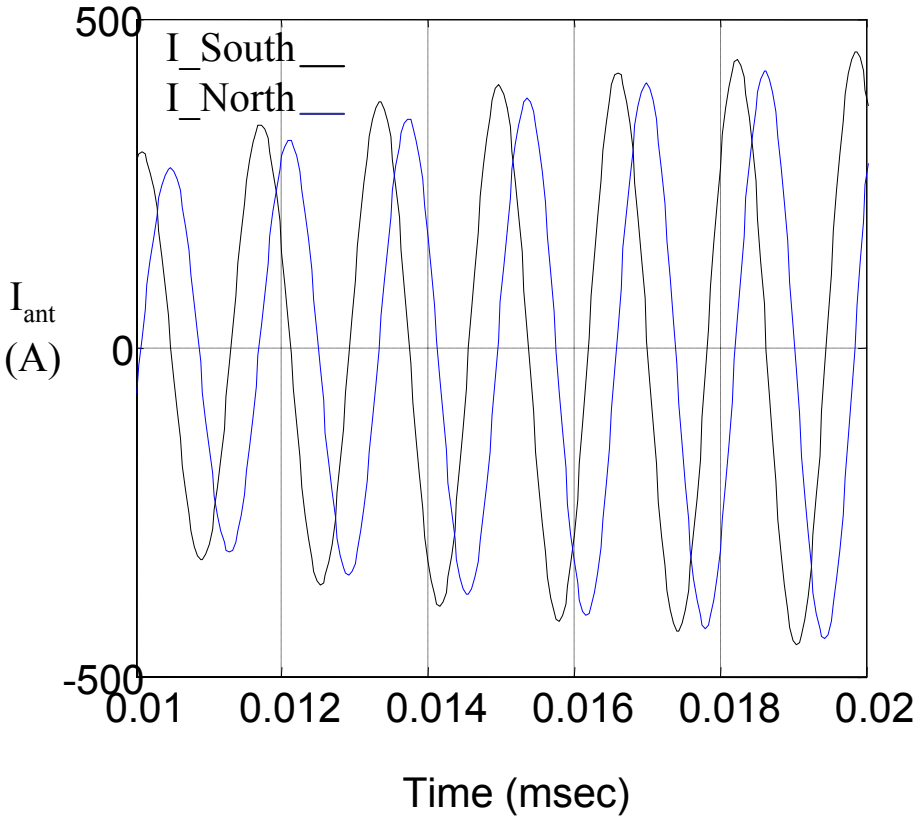
The rotating magnetic field (RMF) that sustains the large-scale dipole currents can be constructed out of copper tubing, and driven by a tuned oscillator (10 –100 kHz) with very high efficiency

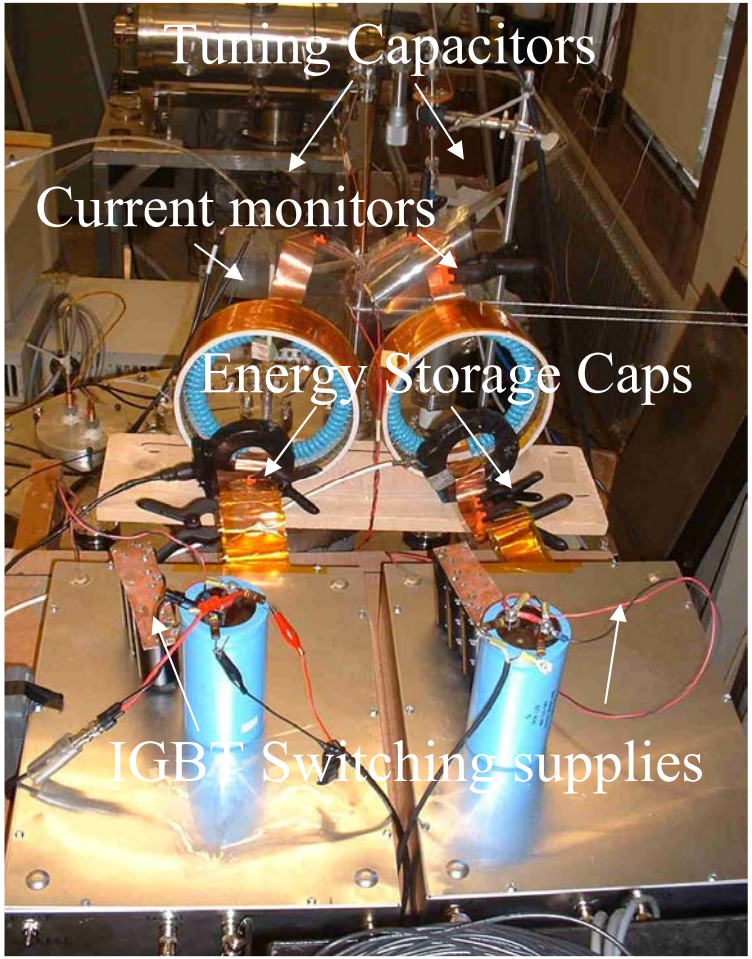




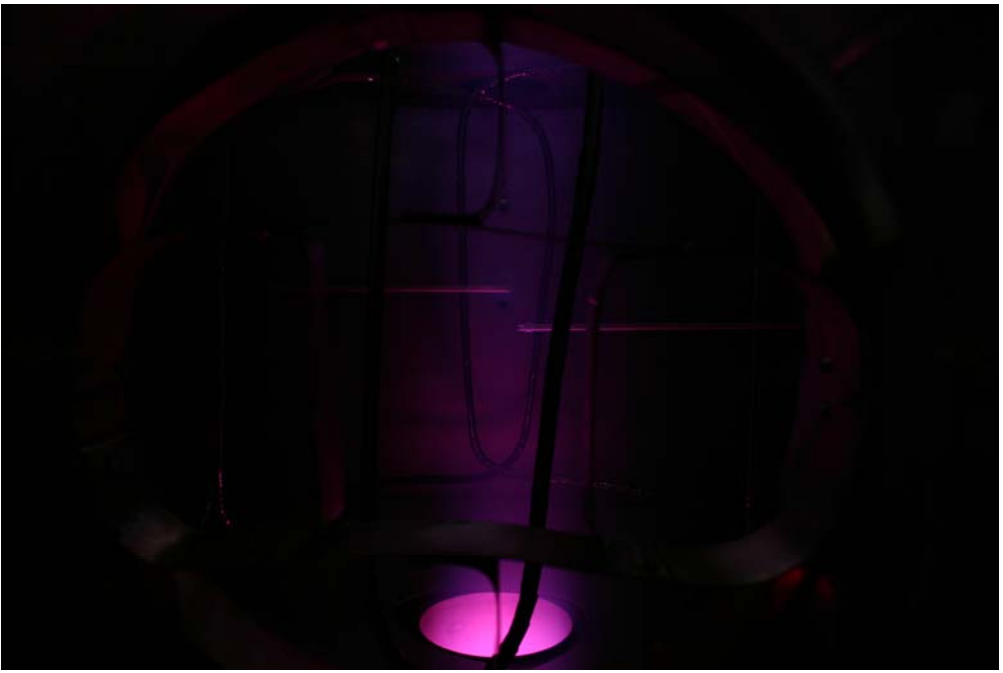
. Even though the plasma may be more resistive than the superconducting wires of the MagSail, the huge difference in cross sectional area that the plasma subtends (km^2 vs. cm^2) minimizes the additional power requiremen

Two-Phase Oscillator Driver Circuits Used to Obtain Rotating Magnetic Field

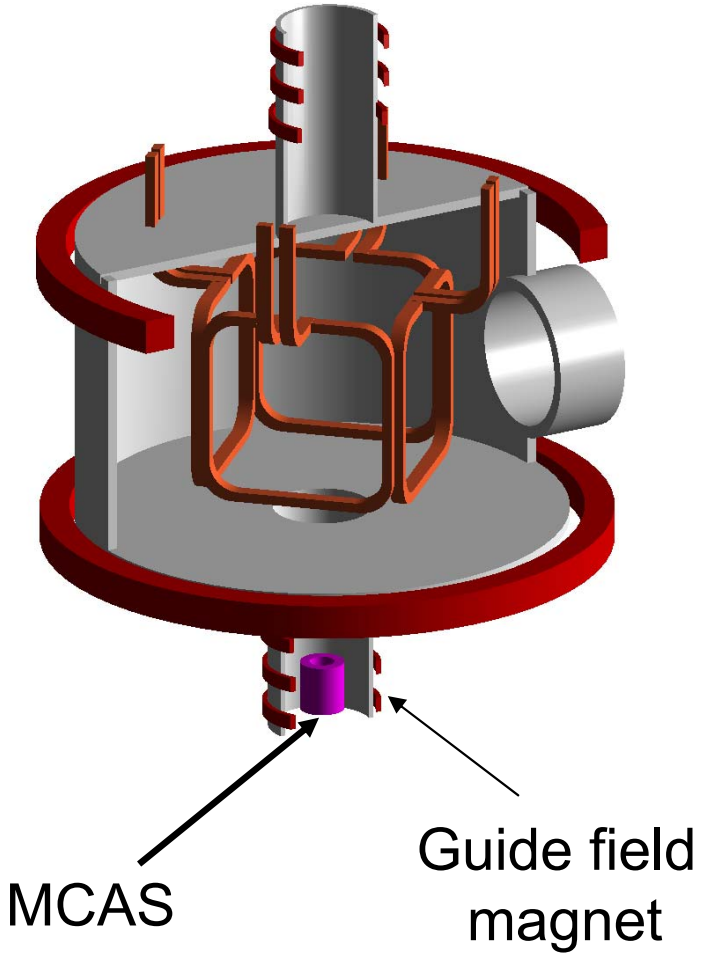




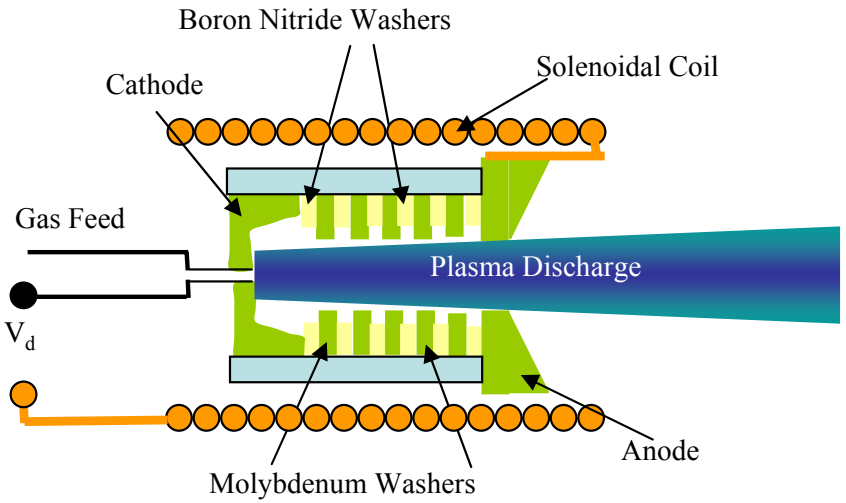
In the Experiment the Initial Plasma was Provided by a Magnetized Cascaded Arc Source (MCAS)

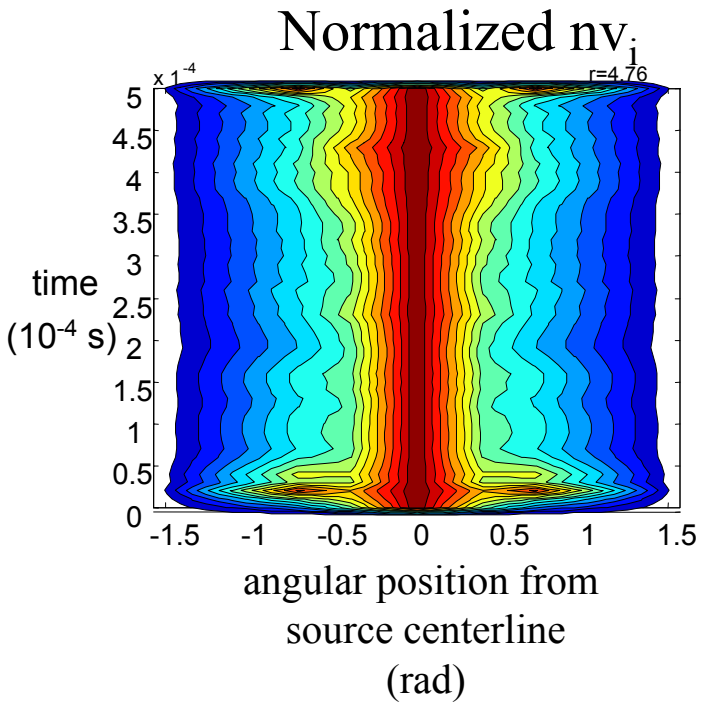


MCAS D_2 Discharge Only (no RMF)



Magnetized Cascaded Arc Source



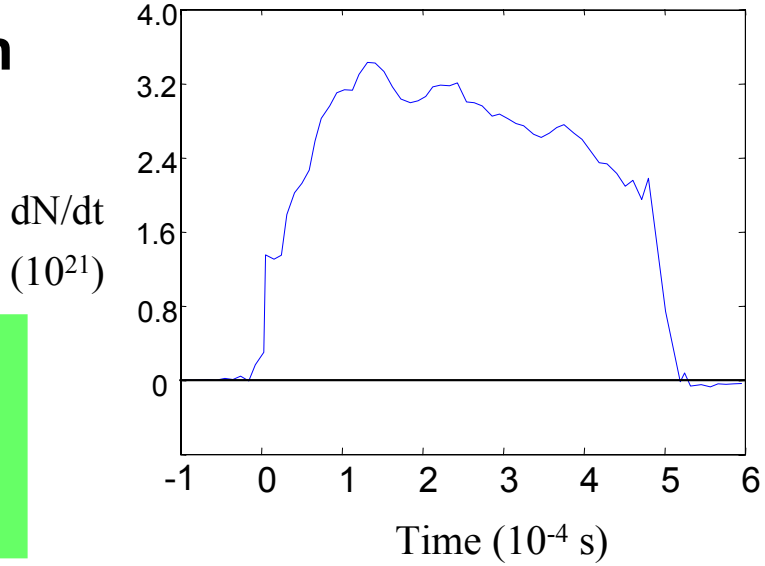


Directed force from plasma gun can be substantial.

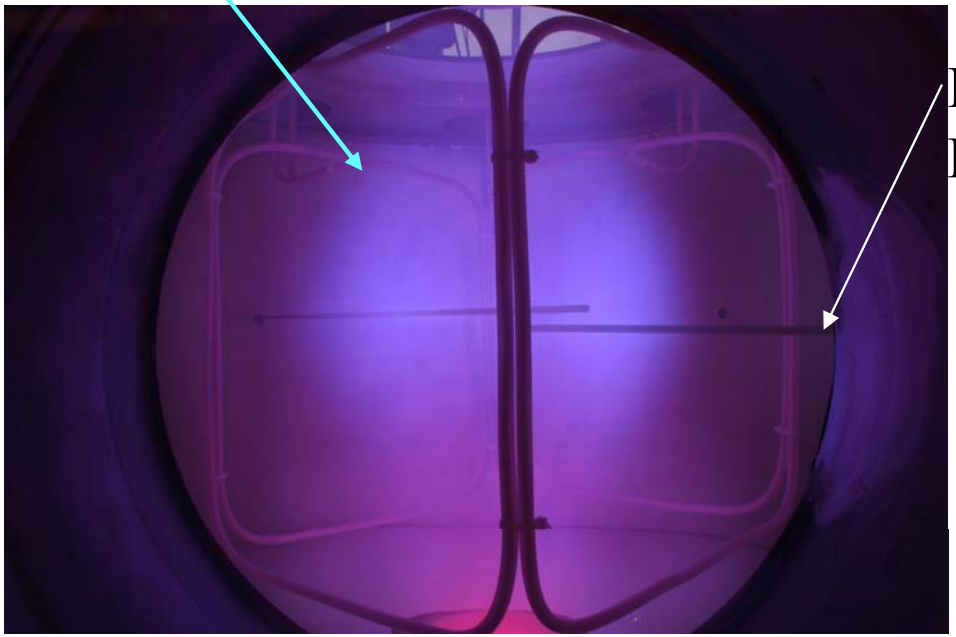
From probe measurements:

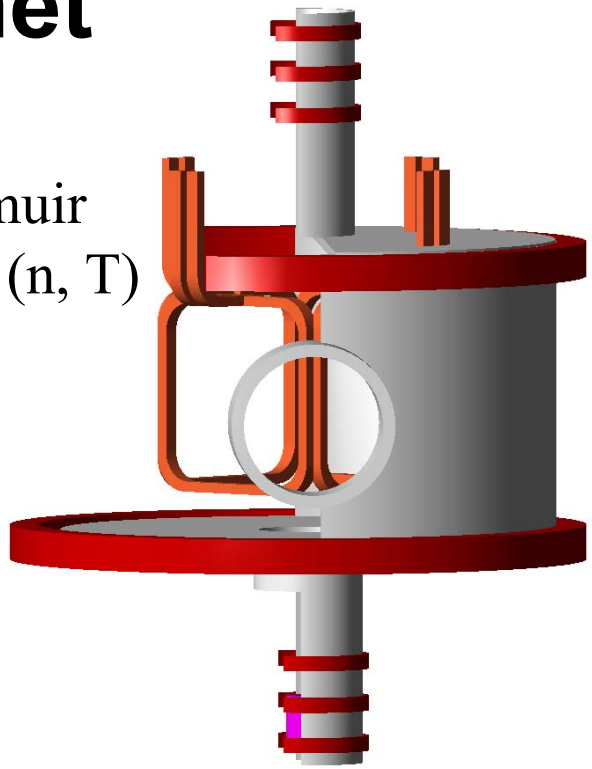
(I_{dis} ~ 2 kA), v_s ~ 35 km/s (H)

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



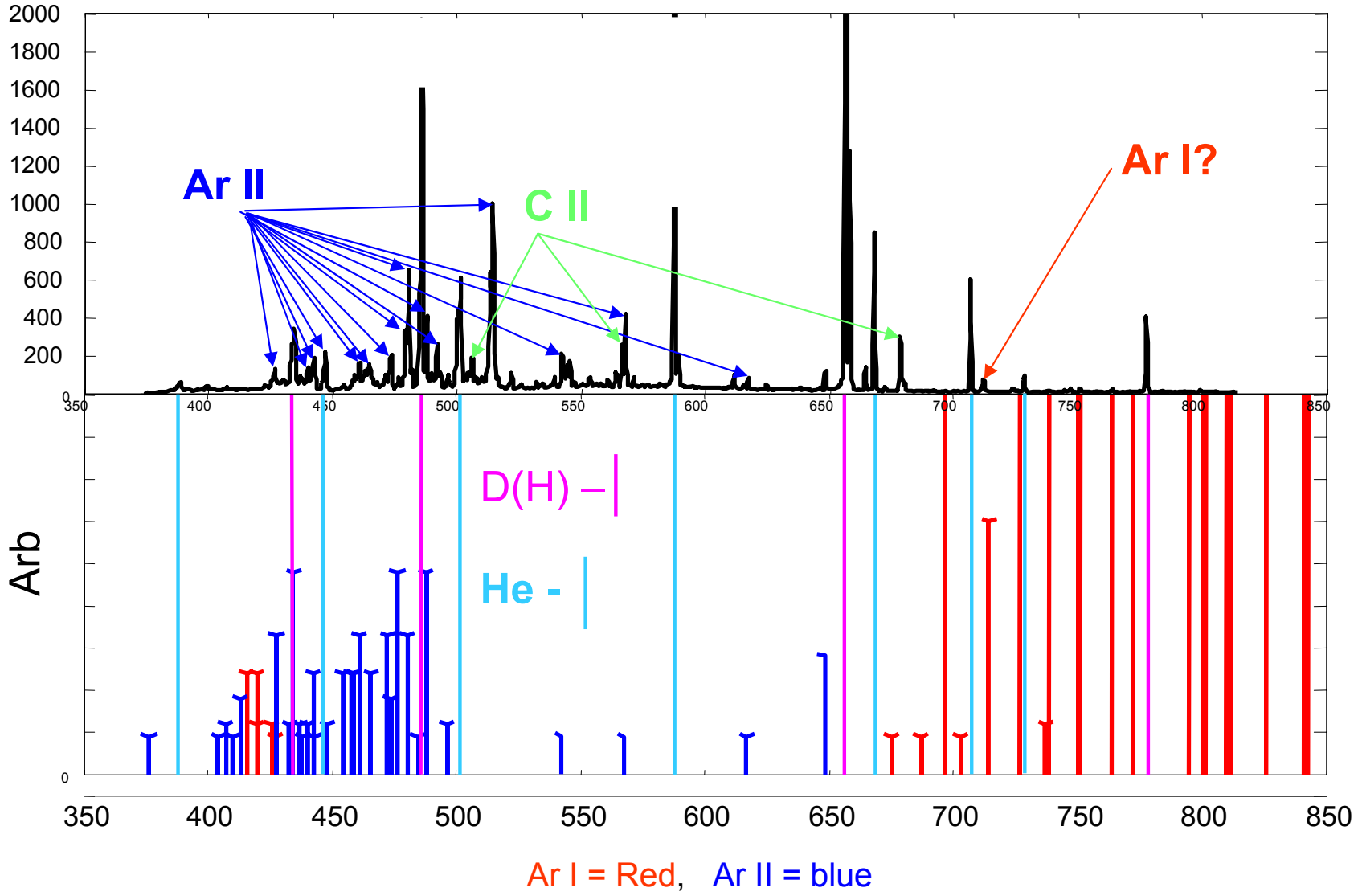
Experimental Verification of the Plasma Magnet





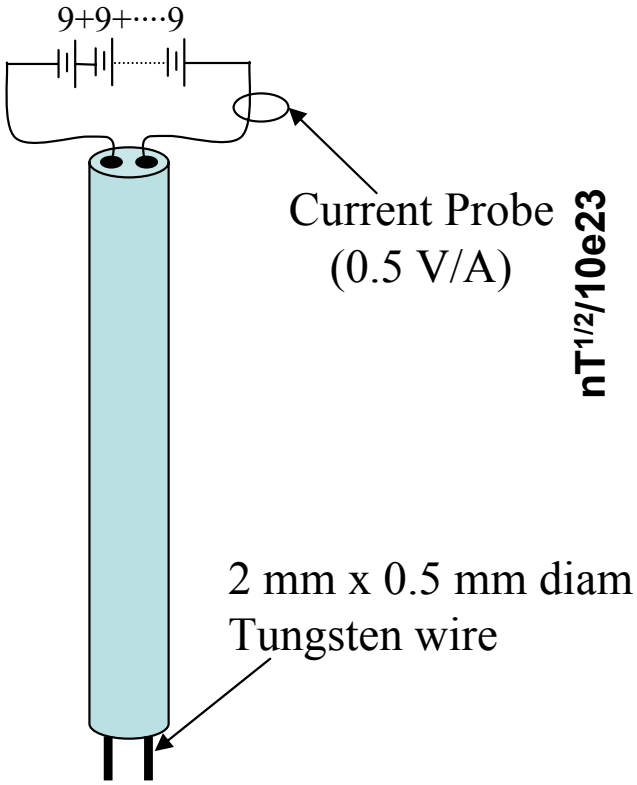
- Up to 10 kA of plasma current have been generated and sustained
- Ring expansion pressure ~ 40 Pa sufficient for 1:100,000 expansion against the solar wind
- Plasma remains linked to RMF antenna in the presence of large axially directed plasma pressure from MCAS (~ 8 Pa)

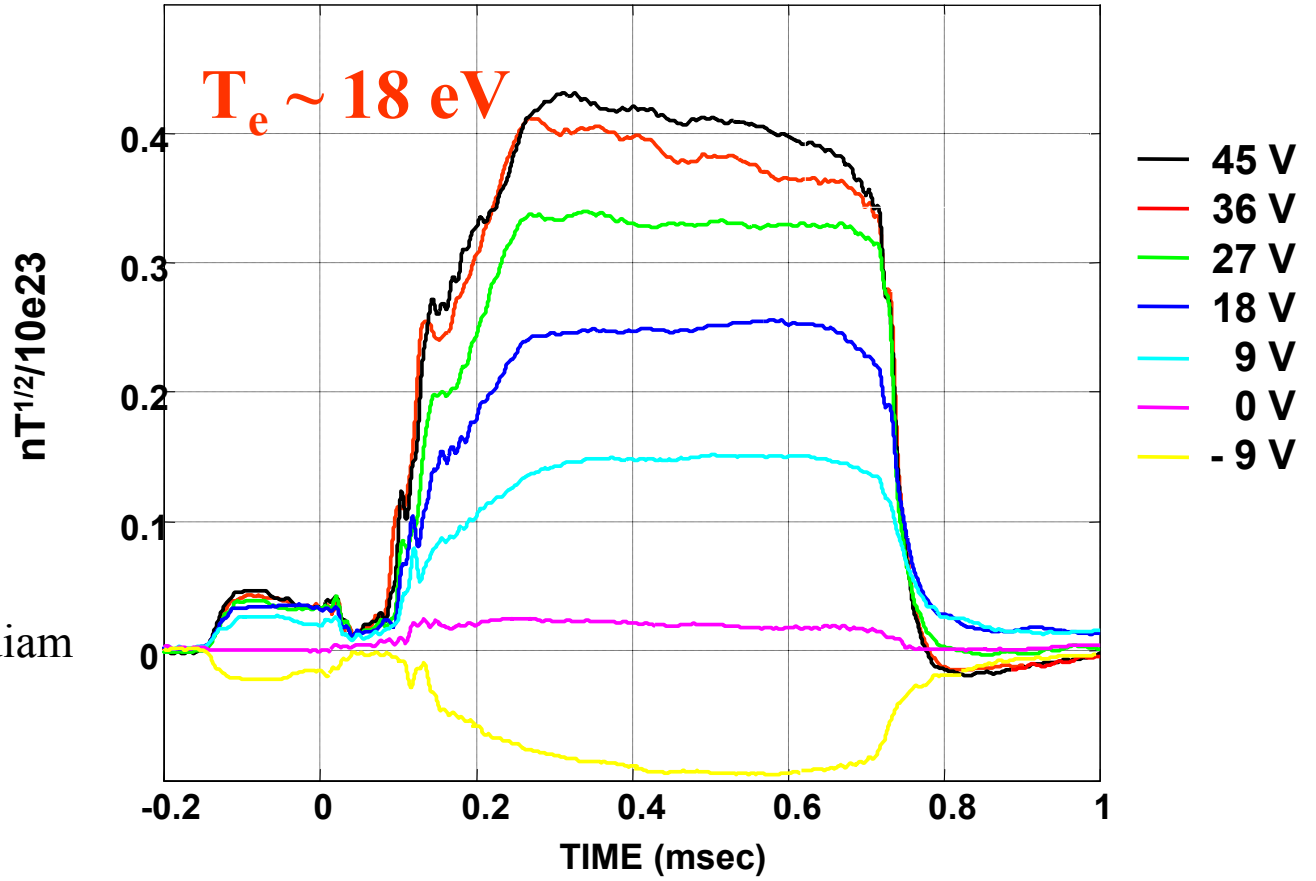
Visible Spectra for Ar Plasma Magnet with Deuterium "Solar Wind"



From pictures and radiation → Plasma is fully ionized

Electron Temperature and Density from Double Langmuir Probe



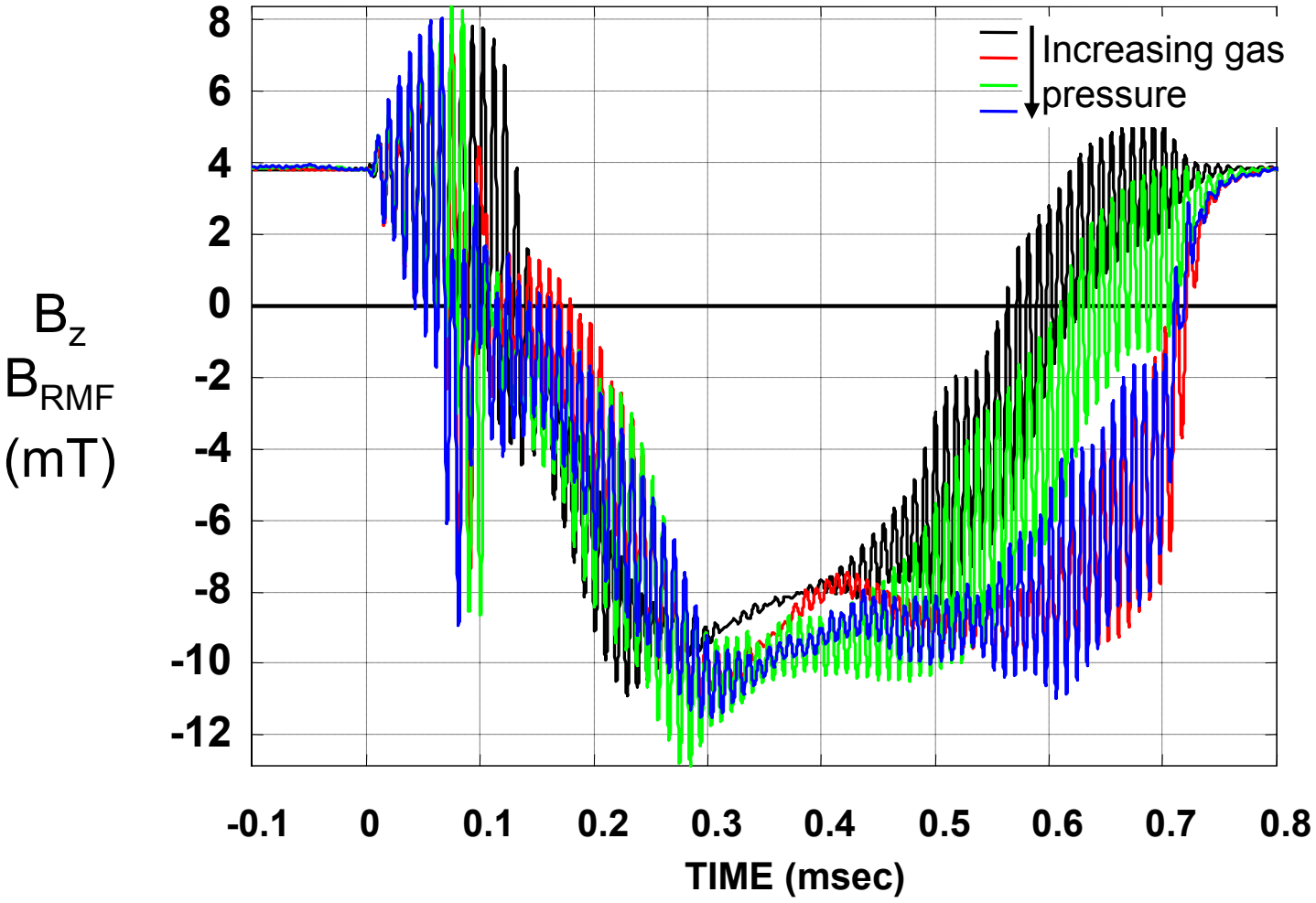


Probe current for symmetric double probe:

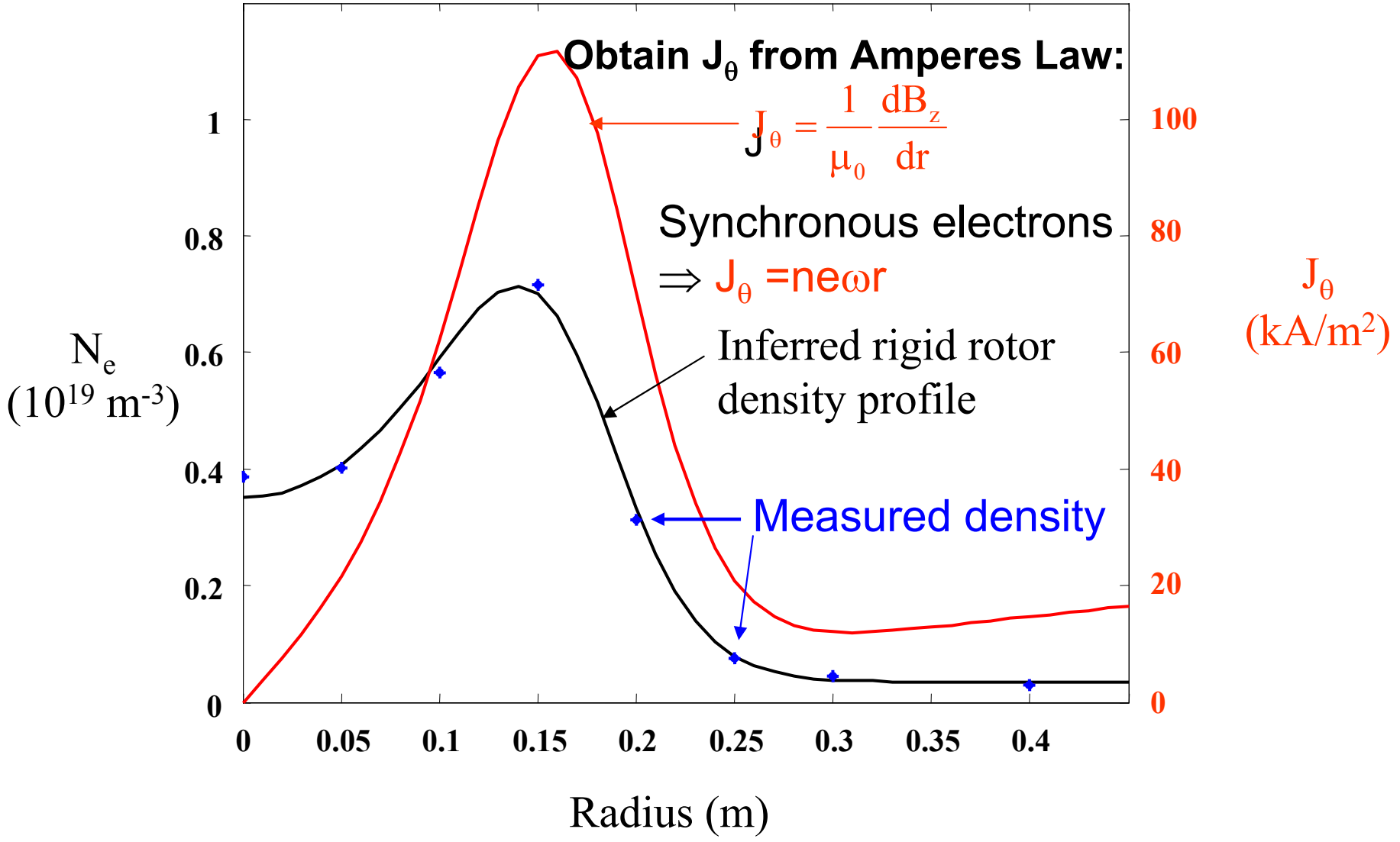
$$I = i_+ \tanh\left(\frac{eV_B}{kT_e}\right), \quad \text{where} \quad i_+ = \frac{1}{2} n A_p \left(\frac{k(T_e + T_i)}{M_i}\right)^{\frac{1}{2}}$$

Magnetic Fields on Axis of the Plasma Magnet

B-dot loop tilted at 45° to pick up both B_z and B_{RMF} simultaneously



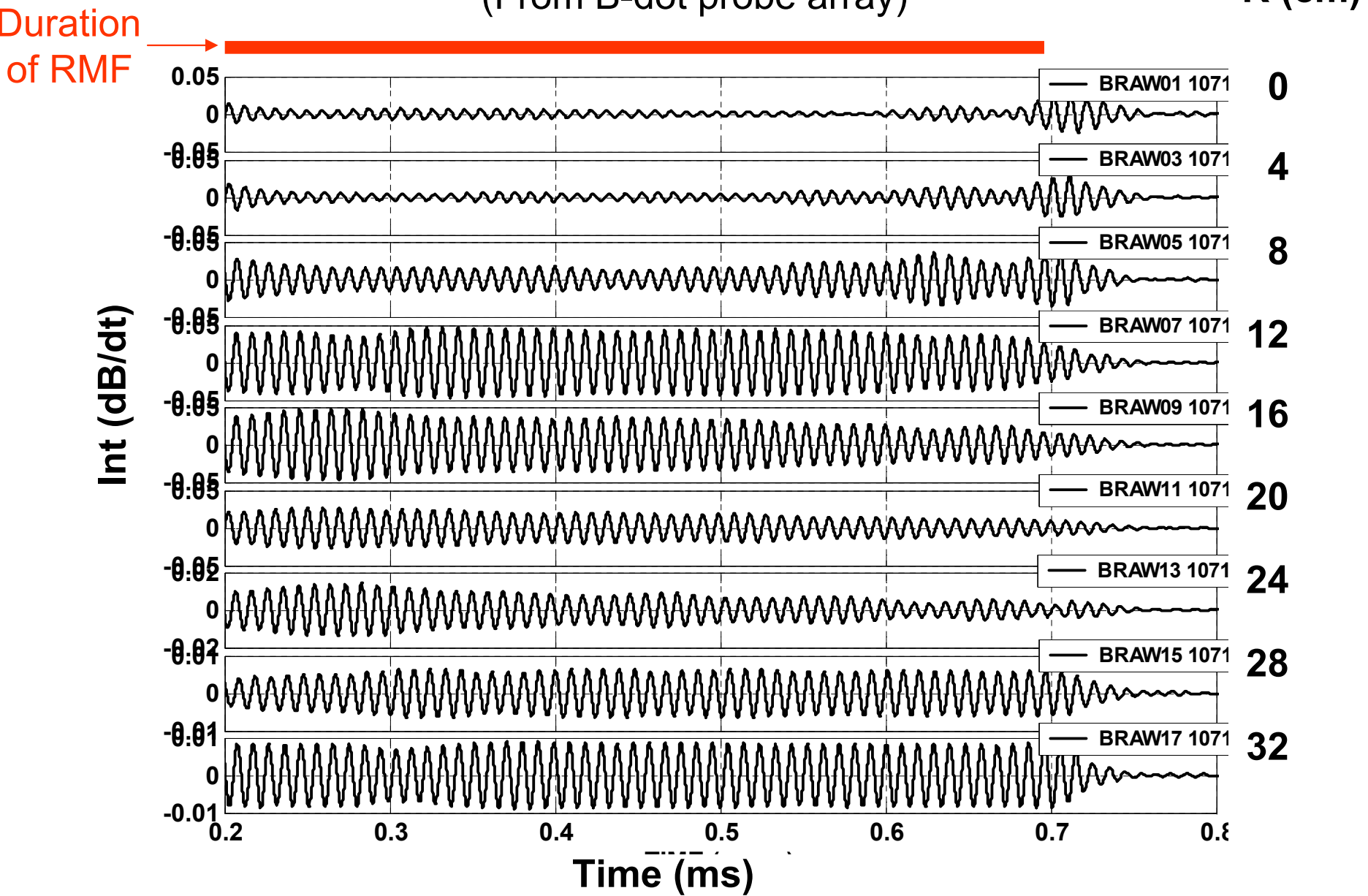
Plasma Magnet Density and Current Profile



Total PM current ~ 8 -10 kA

Measurement of the Rotating Magnetic inside the Plasma Magnet as a Function of Radius

(From B-dot probe array)



Particle confinement in high beta dipolar field

$$\tau_N = \frac{\int n \cdot dvol}{D_\perp \frac{dn}{dr} \int dA} \sim \frac{2\mu_0}{\eta_\perp \beta (3m - m^2)} \left(\left(\frac{r}{R} \right)^{m-3} - 1 \right) r^2$$

where m is the power by which the density decreases (i.e. $1/r^m$) from a characteristic surface that intercepts the equatorial plane at R. With a density fall-off of $1/r^3$ (not critical but less than constant source fed)

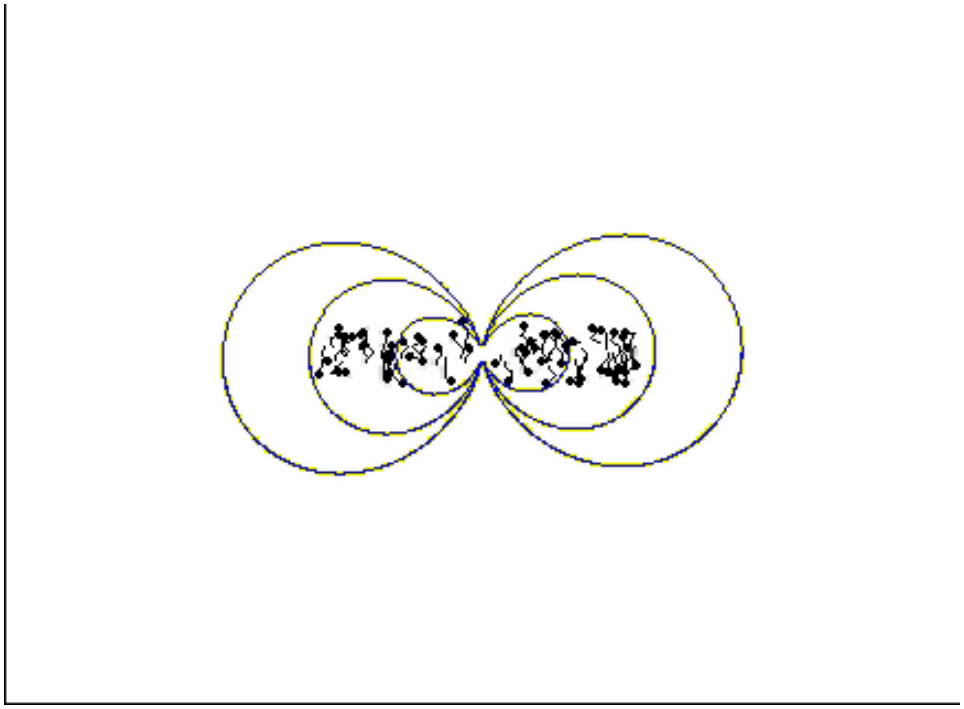
$$N \sim 4\pi R^3 n_0 \ln\left(\frac{r}{R}\right) \qquad \tau_N \sim \frac{2\mu_0}{3\eta_\perp \beta} \ln\left(\frac{r}{R}\right) r^2$$

At high β (~1) and $T_e \sim 20$ eV ($\eta_\perp \sim 1.5 \times 10^{-3}\ T_e(\text{eV})^{-3/2} \Rightarrow$ 17 $\mu\Omega$-m)

For an R = 10 m RMF antenna with sufficient current (density $n_0 \sim 10^{17}$ m^{-3}) to inflate to a r=100 km bubble:

$m_H N =$ 1.8 mg $\qquad \tau_N = 4.5 \times 10^7$ s ~ 1.5 years

Motion of Electrons in Rotating Dipole Field



3-D Calculation of electron motion in rotating magnetic field

Present numerical work is aimed at self consistent motion with Self-generated hall currents

Summary

Phase I Results:

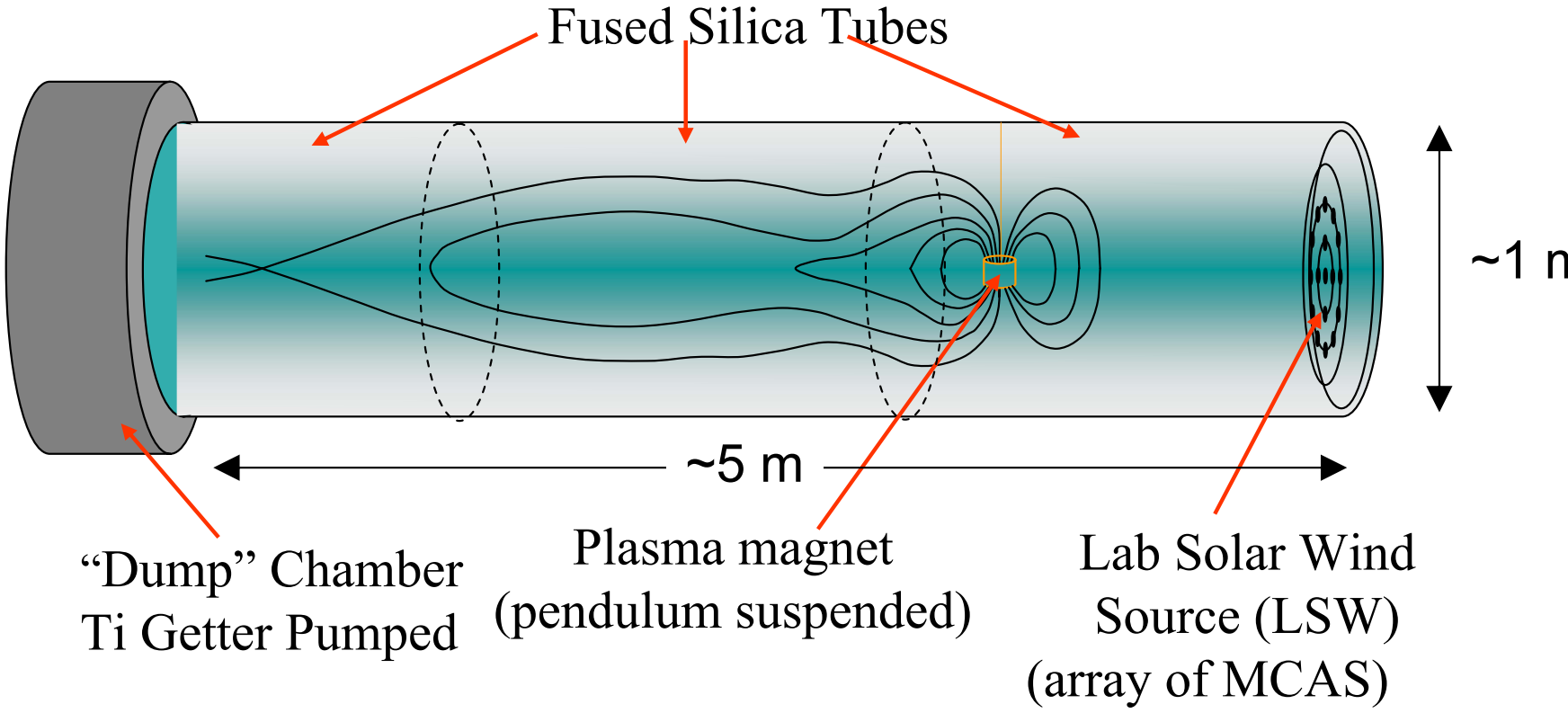
- **A plasma magnet was generated and sustained in a space-like environment with a rotating magnetic field**
- **Sufficient current (~ 10 kA) was produced for inflation of plasma to 10s of km.**
- **Intercepted significant momentum pressure from an external plasma source without loss of equilibrium**
- **Plasma and magnetic pressure forces observed to be reacted on to rotating field coils through electromagnetic interaction**

Further Work on the Plasma Magnet Sail

With successful Phase I testing, it is possible to perform the critical experiments necessary for concept validation in phase II.

- 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 source, 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.

Phase II: Concept Validation: Thrust Measurement And Scalability of Plasma Magnetic Sail



Want to maintain plasma magnet size with smaller antenna to observe expansion

Against Laboratory Solar Wind (LSW) $D_{Antenna} \sim 1/4$ (0.4 m) – 0.1 m

With Constant force expansion/contraction need $\Rightarrow P_{LW} = P_{SW} = 2$ MW

Want ρ_i/R to scale for kinetic effects $\Rightarrow V_{LSW} \sim V_{SW} \sim 40$ km/s