Magnetic Nozzle And Plasma Detachment Experiment

Abstract. High power plasma propulsion can move large payloads for orbit transfer (such as the ISS), lunar missions, and beyond with large savings in fuel consumption owing to the high specific impulse. At high power, lifetime of the thruster becomes an issue. Electrodeless devices with magnetically guided plasma offer the advantage of long life since magnetic fields confine the plasma radially and keep it from impacting the material surfaces. For decades, concerns have been raised about the plasma remaining attached to the magnetic field and returning to the vehicle along the closed magnetic field lines. Recent analysis suggests that this may not be an issue if the magnetic field is properly shaped in the nozzle region and the plasma has sufficient energy density to stretch the magnetic field downstream. An experiment was performed to test the theory regarding the Magneto-hydrodynamic (MHD) detachment scenario. Data from this experiment will be presented.

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) being developed by the Ad Astra Rocket Company uses a magnetic nozzle as described above. The VASIMR is also a leading candidate for exploiting an electric propulsion test platform being considered for the ISS.

Magnetic Nozzle and Plasma Detachment Experiment

D. Gregory Chavers, Chris Dobson, Jonathan Jones, Adam Martin
MSFC, NASA

Roger D. Bengtson, Boris Breizman, Alexey Arifiev
University of Texas at Austin

Jason Cassibry, Branwen Schuttpeltz
University of Alabama in Huntsville

Christopher Deline
University of Michigan

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1

Teams and Tasks (originally)

Manage the project.
Design diagnostics and analyze plasma data from DDEX.
Provide physics requirements for facility configuration and theoretical background and modeling for data interpretation.
Train students.

Design and build the test facility DDEX at MSFC.
Integrate the diagnostics suite into DDEX.
Start experiments on plasma detachment by March 06.

Assess helicon plasma source capabilities.
Provide diagnostics for MSFC experiments.
Perform VASIMR-specific experiments and modeling.

Develop MHD-based nozzle design tool.
Assist in plasma diagnostics integration at MSFC.

2

Outline

- Introduction
- Background
- Plasma Detachment
- Theory
- Model
  - Preliminary model indicates that plasma is super-alfvenic
- Experiment to validate theory and model
  - Experiment designed to match typical plasma conditions
  - Description of experiment
    - Facility
    - Plasma sources
    - Diagnostics
  - Data
    - Density
    - Velocity
- Summary

3

Introduction

- Motivation – High power plasma propulsion can move large payloads for orbit transfer, lunar missions, and beyond with large savings in fuel consumption.

  - For orbit raising or drag compensation – large savings in fuel for long life missions

  - For lunar missions – the savings in fuel is offset by longer trip times

  - For trips to Mars and beyond, high power plasma propulsion is enabling

  - Magnetic fields are used in high power plasma propulsion to guide the plasma and reduce electrode erosion as in Magnetoplasmadynamic (MPD) thrusters

  - Electrodeless plasma propulsion (such as VASIMR) has the advantage of eliminating electrodes and thereby increasing thruster lifetime.
    - A strong guiding magnetic field is required for electrodeless plasma propulsion

4

- Key Issues
  - Plasma source efficiency
  - Plasma acceleration
  - **Plasma detachment**

- The goals of this work are:
  - 1) Demonstrate plasma detachment
  - 2) Quantify magnetic nozzle efficiency
  - 3) Verify computational models and investigate optimization parameters for the magnetic nozzles.
- Project was cancelled after ~25% of resources were received.

5

Plasma detachment issue

- Plasma-based propulsion systems generate thrust by ejecting directed plasma flow.
  - A strong magnetic field is used to guide the plasma.
  - The ejected plasma must break free from the spacecraft to produce thrust.

  - Two scenarios for plasma detachment:
    - Detachment from the magnetic field via recombination or some other mechanism.
    - Detachment with the magnetic field by stretching the field lines along the flow.

vacuum field lines
field lines stretched by the plasma
nozzle wall
strong field
plasma
weak field
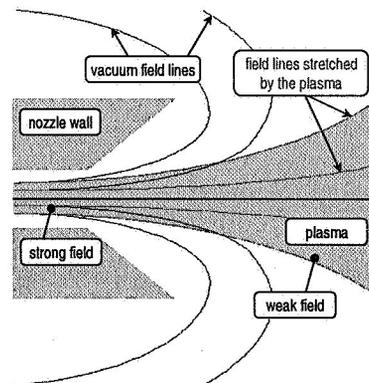
6

Magneto-hydrodynamic detachment concept

- Plasma energy density decreases downstream

- Energy density of the magnetic field decreases faster than the plasma energy density

- Transition from strong field $B^2/8\pi > m_i n_i V_\parallel^2/2$ to weak field $B^2/8\pi < m_i n_i V_\parallel^2/2$ is a transition from sub- to super-Alfvénic flow. This transition is trivial in a conical nozzle with the plasma flow along the magnetic field.
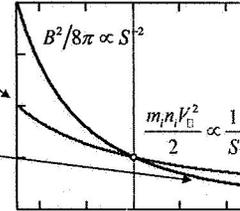
- Plasma flow can stretch the magnetic field lines outward after $B^2/8\pi$ drops below $m_i n_i V_\parallel^2/2$

$B^2/8\pi \propto S^{-2}$

$\dfrac{m_i n_i V_\square^2}{2} \propto \dfrac{1}{S}$

Nozzle cross-section S

Conducting wall

θ_0

Magnetic field lines
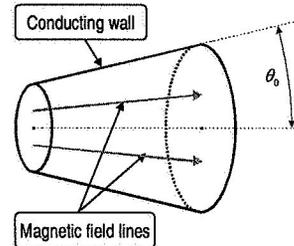
E. N. Parker, Astrophys. J. **128**, 664 (1958).
E. B. Hooper, J. Propul. Power **9**, 757 (1993).

7

Nozzle efficiency

- There are two factors that affect flow directivity:
  - divergence of the nozzle at a half-angle θ_0 ;
  - radial expansion of the outgoing plasma flow at its edge.

Nozzle wall

Moving slice of the plasma plume

Wall current

Plasma current I_φ

$v\delta t$
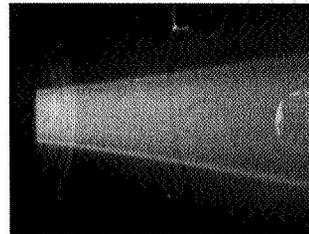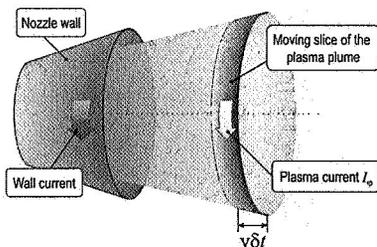
- The wall current attracts the ring current in the plasma
- The attraction force between the two currents reduces the axial momentum of the plasma
- The overall efficiency of the nozzle is $\eta \approx 1 - \dfrac{\theta_0^2}{4} - \dfrac{V_A^2}{2V^2}$

A.V. Arefiev and B.N. Breizman, Phys. Plasmas **12**, 043504-1 (2005).

8

4

Computational Model – MACH2
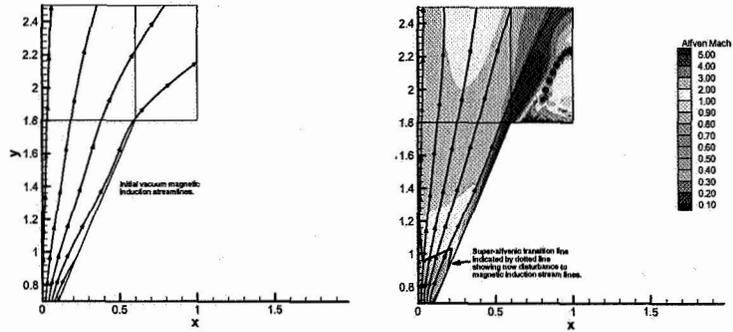
(a) Vacuum Magnetic Field.   (b) Magnetic Field in the Plasma Flow.
Super-Alfvenic flow Straightens the Field Lines Beyond the Nozzle Exit.

9

Plasma conditions for experiment

- Description of Experiment
  - Plasma conditions: start at low beta, sub-alfvenic then transition to high beta, super-alfvenic
    - Incoming flow:

$$m_i V^2 / 2 \approx 10 \, \text{eV}$$
$$n \approx 10^{19} \, \text{m}^{-3}$$
$$B \approx 0.07 \, \text{T}$$
$$V_{\parallel} / V_A \approx 0.1$$
$$P_j \approx 1 \, \text{kW}$$

If radius is 0.02 m, nozzle must be increased to 0.44 m to make

$$V_{\parallel} / V_A \approx 2$$

10

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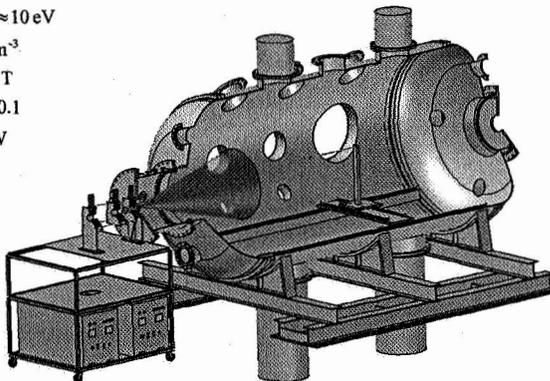
Test Facility

~3 meter diameter X ~5 meter length vacuum chamber
~100,000 L/s vacuum pumping
~30 m³ volume
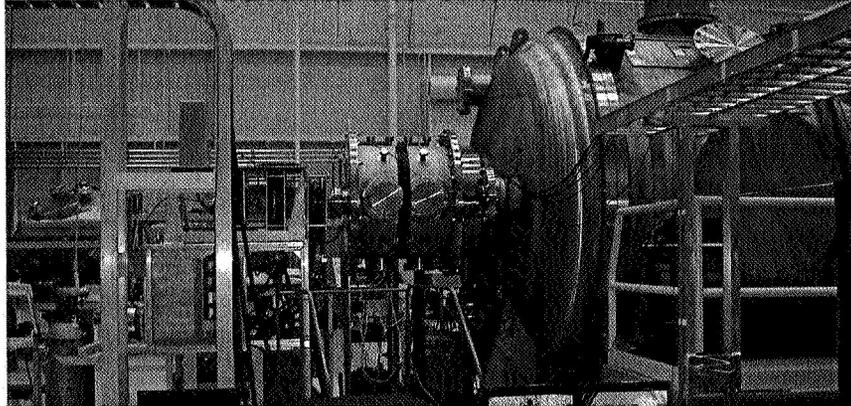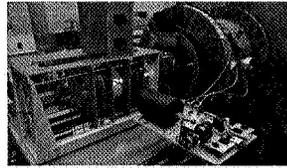
11

Vacuum Magnetic Field Model

Without Earth's B-field included   With Earth's B-field included
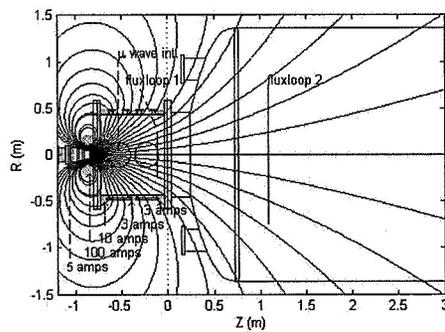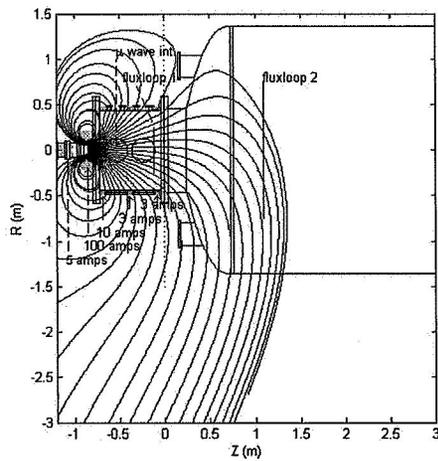
12

Vacuum Magnetic Field

Without Earth's Magnetic Field
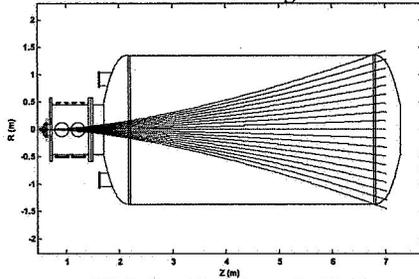
With Earth's Magnetic Field
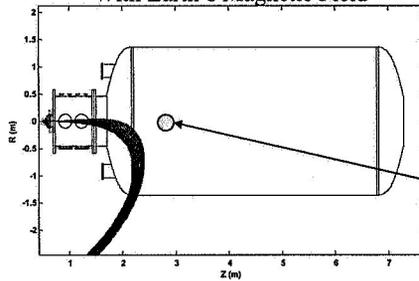
Consider field lines going through source - produces very large dipole
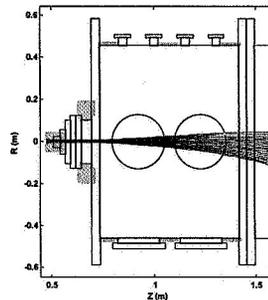
Langmuir probe and microwave interferometer observe plasma at this location – not conclusive that field lines were stretched

13

Plasma Source – Washer Stack Plasma Gun

300 volts, 800 amps (250 amps)
Currently using Argon
Plasma source radius ~ 1 cm

Plasma gun ~15 cm behind baffle plate (2 cm aperture)

Langmuir probe

14

7

Plasma gun using helium

2 cm orifice
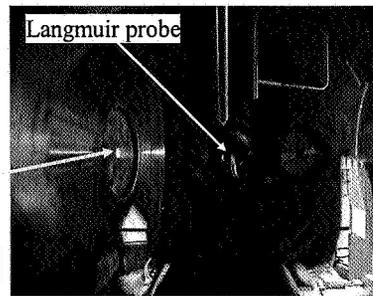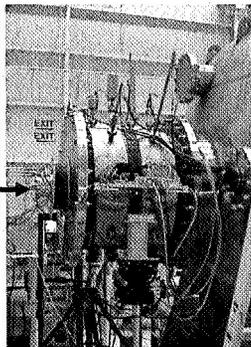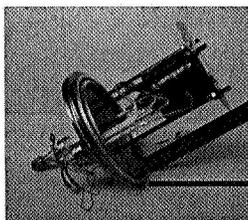
Langmuir probe at Z=-66.7 cm
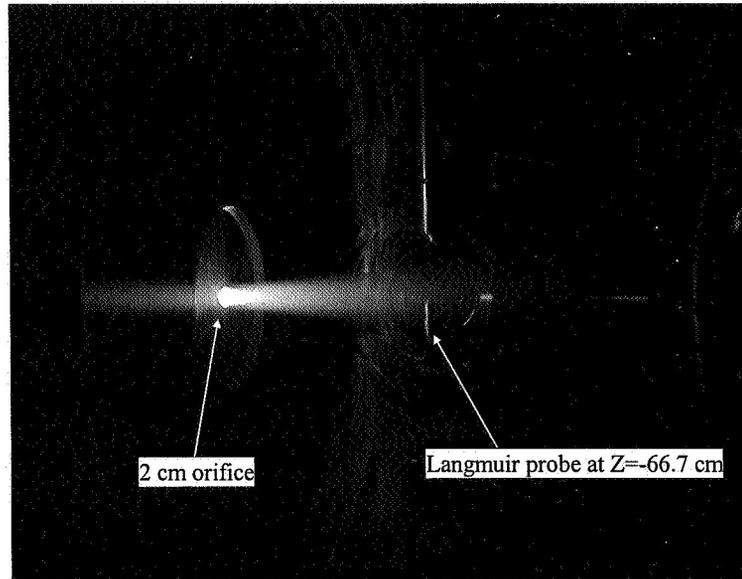
15

Plasma Source - Helicon

- Helicon (shown with small magnets)
 - 1.5 kW Helicon (7 to 15 MHz)
 - 16 kW Helicon (3 to 30 MHz)

1 cm

16

Diagnostics

- Plasma diagnostics
  - Langmuir probes
  - Mach probes
  - Faraday probe
  - Microwave interferometers
  - LIF
  - Electrostatic probes
- Magnetic field
 - Hall probes
  - Bdot probes
  - Flux loop

Plasma gun

Microwave Interferometer
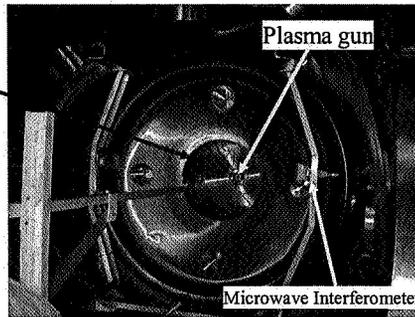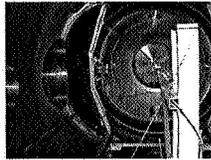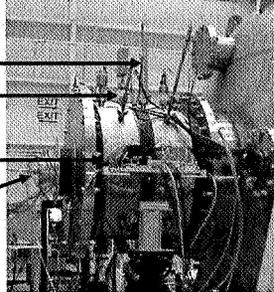
17

Diagnostics
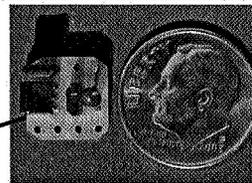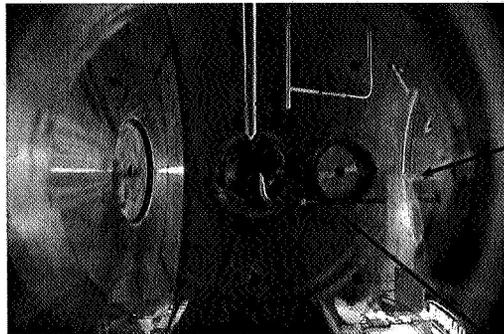
3 axis Hall probe mounted inside glass tube on translation stage.
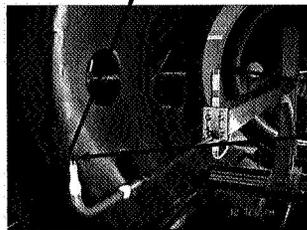
Mach probe

Langmuir probes
-Two probes permit time-of-flight
-Plasma is flowing ~5 km/s

18

9

Density Data

- Density profiles
  - FWHM is 7 cm at B~20G
  - Microwave interferometer provides plasma density at about 2×10^{18} m^{-3}
  - Plasma is magnetized (neutral pressure was reduced)

Gaussian radial profile

Ion saturation current, radial scan

Ion saturation current
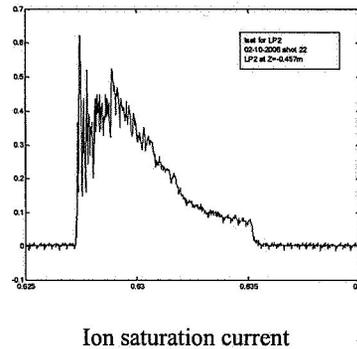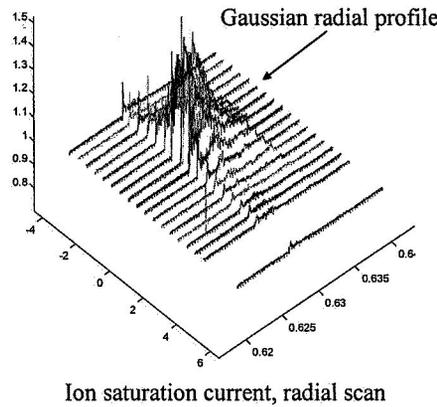
19

Data
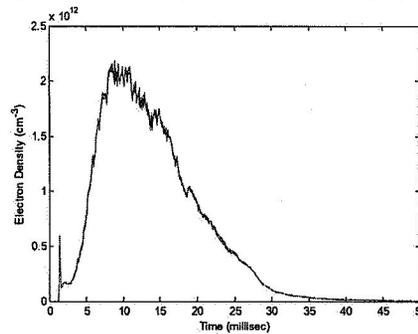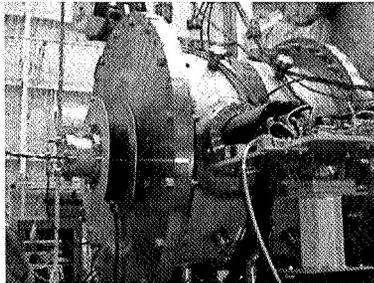
•Vacuum magnetic field model matches Hall probe measurement within a few percent.

•Flux Loop indicates that the plasma is "pushing" magnetic field outward at high gas flow rates
  •This is due to high plasma pressure

20

Density Measurements

- Time dependent areal density measured with the 70, 90, 100 GHz microwave interferometer

- Time dependent probe measurements obtained on successive shots at different radial positions to determine profile shape.

- The interferometer and probe data were integrated over each pulse to obtain time average areal density and probe voltage (Isat) respectively.

- The density was found by relating the probe data to the interferometer in the following manner

$$\text{Measured Quantities} \begin{cases} Isat(x,z,t) & \longleftarrow \quad \text{Measured with the Langmuir probe} \\ N_e(z,t) = \int n_e(x,z,t)dx & \longleftarrow \quad \text{Measured with the interferometer} \end{cases}$$

$$\bar{I}(x,z) \equiv \frac{1}{\Delta t} \int Isat(x,z,t)dt$$

$$\bar{N}_e(z) \equiv \frac{1}{\Delta t} \int N(z,t)dt$$

$$\bar{n}_e(x,z) \equiv \frac{\bar{N}_e(z)\,\bar{V}(x,z)}{\int \bar{I}(x,z)dx}$$

21

Preliminary Density Profile at Z = - 66.7 cm

Langmuir probe at Z = - 66.7 cm

FWHM = 2.595 cm

Langmuir probe at Z = - 7 cm

FWHM = 14.569 cm

22

11
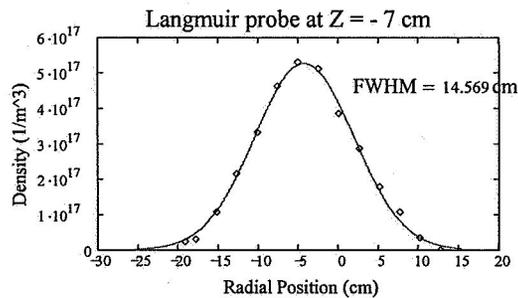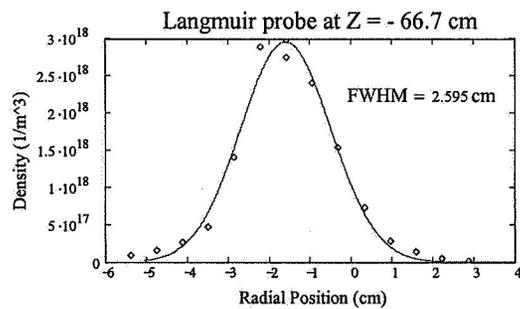
Summary

- Facility is operational
- Experiment is operational
- Diagnostics operational
- Preliminary data suggests that the plasma is magnetized when the neutral input pressure in minimized (collisions are reduced)
- Plasma is observed at 2 meters downstream
- Further analysis of data is required

23