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. Electroless high power, lifetime of the thruster becomes an issue. Electroless devices with magnetic fields confine the plasma radially and keep it from impacting the material surfaces. For decades, concerns have been raised about the vehicle 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 has sufficient energy density to stretch the magnetic field downstream. An experiment was performed to test the theory regarding the Magnetohydrodynamic (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

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July 17, 2006

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.
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

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 Magnetoplasmodynamic (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
**Background**

- **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.

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**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.
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 $B^2/8\pi > m_n n V_i^2/2$ to weak field $B^2/8\pi < m_n n V_i^2/2$ 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 $m_n n V_i^2/2$.


Nozzle efficiency

- There are two factors that affect flow directivity:
  - divergence of the nozzle at a half-angle $\theta_0$;
  - radial expansion of the outgoing plasma flow at its edge.
- 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
  $$\eta \approx 1 - \frac{\theta_0^2}{4} - \frac{V_i^2}{2V^2}$$

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.

Plasma conditions for experiment

- Description of Experiment
  - Plasma conditions: start at low beta, sub-Alfvenic then transition to high beta, super-Alfvenic
  - Incoming flow:
    \[ \frac{n e V}{2} = 10 \text{ eV} \]
    \[ n = 10^9 \text{ m}^{-3} \]
    \[ B = 0.07 \text{ T} \]
    \[ \frac{V_i}{V_a} = 0.1 \]
    \[ P_i = 1 \text{ kW} \]

If radius is 0.02 m, nozzle must be increased to 0.44 m to make
\[ \frac{V_i}{V_a} \approx 2 \]
**Test Facility**

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

**Vacuum Magnetic Field Model**

Without Earth's B-field included

With Earth's B-field included
Vacuum Magnetic Field

Without Earth's Magnetic Field

Consider field lines going through source - produces very large dipole

With Earth's Magnetic Field

Langmuir probe and microwave interferometer observe plasma at this location - not conclusive that field lines were stretched

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)
Plasma gun using helium

Plasma Source - Helicon

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

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

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
Density Data

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

Ion saturation current, radial scan

Ion saturation current

Gaussian radial profile

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
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:

\[
\text{Measured Quantities} \quad \begin{cases} 
  \text{Isat}(x, z, t) \\
  \text{N}_e(x, z, t) = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} \text{Isat}(x, z, t) dt \\
  \bar{N}_e(x, z) = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} N(x, z, t) dt \\
  \bar{N}_e(x, z) = \frac{\bar{N}_e(x, z) \bar{V}(x, z)}{\bar{I}(x, z)} dx 
\end{cases}
\]

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
Summary

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