Appendix H

LOS ALAMOS NEP RESEARCH IN ADVANCED PLASMA THRUSTERS

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PLASMA THRUSTER RESEARCH

Los Alamos has initiated research in advanced plasma thrusters that capitalizes on Laboratory capabilities in plasma science and technology

THE PROGRAM GOAL:

- Elucidate the scaling issues of MPD thruster performance in support of NASA's MPD thruster development program

THE PROGRAM OBJECTIVE:

- Address multi-megawatt, large scale, quasi-steady-state MPD thruster performance
ADVANCED PLASMA THRUSTERS
Active Research Activities

• A CTX coaxial plasma gun, with tungsten-coated electrodes, is being operated as a function of current, gas pressure, gas type, applied axial magnetic field, and electrode polarity.

• The steady-state properties of nozzle-based coaxial plasma guns are being modeled by an evolving magnetic Bernoulli equation that provides analytic predictions for thruster power, mass flow rate, thrust, and specific impulse.

• Research Results:
  * A new quasi-steady-state operating regime has been obtained at SEI-relevant power levels (5 to 10 MW), that enables direct coaxial gun - MPD comparisons of thruster physics and performance.
  * Radiative losses are negligible
  * Operation with an applied axial magnetic field shows the same operational stability and exhaust plume uniformity benefits seen in MPD thrusters.
  * Observed gun impedance is in close agreement with the magnetic Bernoulli model predictions.
  * Spatial and temporal measurements of magnetic field, electric field, plasma density, electron temperature, and ion/neutral energy distribution are underway.
  * Model applications to advanced mission logistics are underway.
ELECTROMAGNETIC THRUSTERS: $\mathbf{J} \cdot \mathbf{B}$ DRIVES $\rho \dot{v}_z$

**MPD THRUSTERS**

- $I = \text{few kA}$
- $V = 100 \text{ volts}$
- $n = 10^{20} \cdot 10^{21} \text{ m}^{-3}$

**COAXIAL GUNS**

- $I = 50-100 \text{ kA}$
- $V = \text{few} 100 \text{ volts} - \text{few kV}$
- $n = 10^{20} \cdot 10^{21} \text{ m}^{-3}$
COAXIAL GUN DISCHARGE # CTX19645

Diagram

Visible Emission

Intensity Contours (0–255)
COAXIAL GUN DISCHARGE # CTX19659

Diagram

Visible Emission

Intensity Contours (0–255)

ORIGINAL PAGE IS OF POOR QUALITY
DEFLAGRATION + NOZZLE = THRUST

BUILT-IN NOZZLE

MAGNETICALLY-FORMED NOZZLE
PLASMA THRUSTER RESEARCH
Spatial Field Measurements

3-D Spatial $|B|$ plot
ADVANCED PLASMA THRUSTERS
The Importance of Scale

- We hypothesize that scale is important to optimize MMW mission applications.

- We hypothesize that scale may directly affect the MMW thruster performance characteristics:
  - lower current density
  - smaller gradient scale lengths
  - transition from resistive to more "ideal like" MHD operation
  - lower plasma turbulence - higher efficiency

ADVANCED PLASMA THRUSTERS
The Importance of Scale

Thrust power as a function of I and r

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ADVANCED PLASMA THRUSTERS
Envisioned Experimental Program

NEAR-TERM

- Characterize QSS power balance at large scale, MMW
  - Electrode Losses
  - Radiation
  - Axial, radial transport
- Compare global loss estimates with locally determined power balance

FARTHER-TERM

- Achieve QSS and mass-flow steady state
- Benchmark power balance
- Address performance optimization
  - electrode configuration
  - nozzle configuration (magnetic)
  - spatial scale
SCALING ISSUES FOR MPD THRUSTERS

- Possible Reasons for Scaling with R -
  - Mission Scaling
  - Transport Scaling
  - Macroscopic Stability
  - Microscopic Stability
  - Optimization of Thruster Efficiency
SCALING ISSUES FOR MPD THRUSTERS

- **Mission Scaling** -

\[
\begin{align*}
C & \quad \text{time floats} \\
\rightarrow u & \quad P \quad \text{time constrained} \\
\uparrow I_{sp}
\end{align*}
\]

In either case,

- \( M_{En} \), \( M_{pr} \), \( M_{cp} \) all scale with \( m_{pr} \),

where

\[
m_{pr} = \frac{1}{2} N_{th} S_0 A_0 f \quad (f = \frac{V_0}{V_e})
\]

Note: \( m_{pr} \sim N_{th} S R^2 \quad (\text{fixed } \frac{A}{R}) \)

- \( I \sim R P^* \) for fixed \( I_{sp} \)

- \( m_{pr} \): "specific mass of the propellant"
SCALING ISSUES FOR MPD THRUSTERS

Transport Scaling

May be related to the mechanism of plasma production and "ingestion".
Scaling Issues for MPD Thrusters

- Plasma Production and Heating -

Model: "Sand dropped on Conveyor Belt"

Assume $T_e = T_i$

Approach: Boltzmann Equation with Source

Get:

$$\left( \frac{d}{dt} = \frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla} \right)$$

$$\frac{2}{\gamma - 1} \frac{dT}{dt} + 2T \vec{v} \cdot \vec{v} =$$

= Ohmic Heating + Viscous Heating

- Thermal Conduction Loss

$$+ n_0 \langle \sigma - \nu \rangle^o \left[ \frac{1}{2} m_\nu \vec{V}^2 - \frac{2}{\gamma - 1} T - e_i \right]$$

$$- n_0 \langle \sigma - \nu \rangle^o e_i \left[ \frac{1}{2} m_\nu \vec{V}^2 - \frac{2}{\gamma - 1} T - (e_i - e_\nu) \right]$$

where $\frac{1}{2} m_\nu \vec{V}^2$ means $\frac{1}{2} m_\nu (\vec{V} - \vec{V_m})^2$. 

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SCALING ISSUES FOR MPD THRUSTERS

- Transport Scaling -

- Mass Transport ($\omega_{ce} < \omega_e$)
  \[
  \frac{t_e}{t_i} \sim R_{mag} \sim \left( \frac{V_e}{D_i} \right) \sim T \frac{I}{R} \sim \left( \frac{I}{RP^{1/2}} \right) R
  \]

- Mass Transport ($\omega_{ce} > \omega_e$)
  \[
  \frac{V_t \cdot t_e}{\Delta} \sim \frac{c}{\omega_{pi}} \quad [\text{Ions carry some current.}]
  \]

- Heat Transport by classical ions
  \[
  \delta \left[ \frac{MW}{m^2} \right] \quad (\text{next slides})
  \]
SCALING ISSUES FOR MPD THRUSTERS

PREDICTIONS FROM "CONVEYOR BELT" MODEL OF ION HEATING (HYDROGEN)

\[ T_i (eV) = 5.0 \times 10^{10} \left( \frac{I^2}{n^2r^2} \right)_{MKS} \]

\[ \frac{\omega_{ci}}{\nu_{ii}} = 4.6 \times 10^{29} \left( \frac{I^4}{n^{5/2}r^4} \right)_{MKS} \]

\[ \frac{\omega_{ce}}{\nu_e} = 30 \frac{\omega_{ci}}{\nu_i} \quad \text{assuming } T_e = T_i \]

\[ q_i (MW/m^2) = 6.3 \times 10^{33} \left( \frac{I^7}{n^{7/2}r^8} \right)_{MKS} \frac{1}{1 + 2 \left( \frac{\omega_{ci}}{\nu_{ii}} \right)^2} \left( \frac{r}{\Delta} \right) \]

\[ R_v = 0.58 \times 400 \times 10^{-40} \left( \frac{n^{3.5}}{I^4} \right)_{MKS} \left( \frac{\Delta}{r} \right) \left[ 1 + 3 \left( \frac{\omega_{ci}}{\nu_{ii}} \right)^2 \right] \]
SCALING ISSUES FOR MPD THRUSTERS

\[ Q_{i,j} := Q_i(I_1, n_1, r_1) \]

\[ I_0 = 5 \times 10^3 \]
\[ I_0 = 5.5 \times 10^4 \]
\[ r_0 = 0.01 \]
\[ r_0 = 0.51 \]
\[ n_0 = 3 \times 10^{20} \]

\[ q_x \left[ \frac{MW}{m^2} \right] \]

(Hydrogen)

\[ Q_{I,0} = 15.448 \]
\[ Q_{0,0} = 2.3 \times 10^{-10} \]
\[ Q_{10,0} = 1.406 \]
\[ Q_{10,10} = 0.004 \]
SCALING ISSUES FOR MPD THRUSTERS

- Macroscopic Stability -

The viscous Reynolds number (with magnetized ions) may become large and may thereby induce turbulent channel flow.
Scaling Issues for MPD Thrusters

- Turbulent Convection -

\((w_{ci} > \nu_a\text{ case})\)

Viscous Reynolds number: \(\frac{V \Delta}{D_v} = \mathcal{R}_v\)

Ion Shear Viscosity: \(\frac{1}{7} \frac{\nu^2_{thi}}{\frac{\nu_a}{\omega_{ci}^2}} = D_v\)

\(\nu_a = \text{const.} \times m \times T^{-3/2}\)

Hence \(\mathcal{R}_v = \text{const.} \times \Delta \times \left( V \frac{B^2}{m} \frac{1/2}{T_i} \right)\)

If \(T_i\) "does scale" (like \(V^2\))

then \(\mathcal{R}_v = \text{const.} \times \Delta \times V^x \sim \left( \frac{I^2}{\dot{M}} \right)\)
Scaling Issues for MPD Thrusters

\[
RV_{1,1} = \log [RV[I, n, r]]
\]

- \( I = 5.10 \)
- \( r = 0.01 \)
- \( n = 2.10 \)

- \( I = 5.5 \cdot 10^3 \)
- \( r = 0.51 \)

- \( I = 10 \)
- \( r = 0.0 \)

- \( n = 10 \)

RV1 = 2.964

RV1 = 6.107

RV1 = 7.13

RV1 = 2.277

\[ \theta = 20^\circ \]

Large Guns

MPD
SCALING ISSUES FOR MPD THRUSTERS

--- Microscopic Stability ---

\[ V_{tr, R} \leq v_{thi} \text{ (threshold)} \]

equivalent to

\[ \frac{I^2}{\dot{M}} \leq \frac{4 \pi}{\mu_0} \frac{R}{(c/\omega_i)} v_{thi} \]

If \( (T_x \text{ does not scale with } v^2) \)

Then \( \frac{I^2}{\dot{M}} \leq \text{approx. const.} \)

If \( (T_x \text{ scales with } V^2 \text{ [hi I]} ) \)

Then \( \frac{I}{\dot{M}} \leq \text{const.} \left[ \text{observed at hi I} \right] \)