Appendix H

LOS ALAMOS NEP RESEARCH IN ADVANCED PLASMA THRUSTERS

Kurt Schoenberg and Richard Gerwin

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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: $J_r B_\phi$ DRIVES $\rho \dot{v}_z$

**MPD THRUSTERS**

I = few kA  
v = 100 volts  
$n = 10^{20} - 10^{21}$ m$^{-3}$

**COAXIAL GUNS**

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

Diagram

Visible Emission

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

Diagram

Visible Emission

Intensity Contours (0-255)
DEFLAGRATION + NOZZLE = THRUST

BUILT-IN NOZZLE

MAGNETICALLY-FORMED NOZZLE
PLASMA THRUSTER RESEARCH
Spatial Field Measurements

3-D Spatial $|B|$ plot
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

Thrust power as a function of I and r
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 -

- time floats
- time constrained

In either case,

- $M_{En}$, $M_{pr}$, $M_{cp}$ all scale with $m_{pr}$

where $m_{pr} = \frac{1}{2} N_{th} S_0 A_0 f \left( f = \frac{V_0}{V_e} \right)$.

Note: $m_{pr} \sim N_{th} P R^2 \left( \text{fixed } \frac{A}{R} \right)$

- $I \sim R P^{\frac{1}{2}}$ 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: \[ \frac{2}{\gamma - 1} \frac{dT}{dt} + 2T \vec{V} \cdot \vec{V} = \]

= Ohmic Heating + Viscous Heating

- Thermal Conduction Loss

\[ + n_0 \langle \sigma n \rangle e \left[ \frac{1}{2} m_e V^2 - \frac{2}{\gamma - 1} T - e_i \right] \]

\[ + n_1 \langle \sigma n \rangle \left[ \frac{1}{2} m_e V^2 - \frac{2}{\gamma - 1} T - (e_i - e_* ) \right] \]

ionization of excited states:

\[ - \frac{n_0 \langle \sigma n \rangle}{m_1 \langle \sigma n \rangle} e_* \]

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

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SCALING ISSUES FOR MPD THRUSTERS

- Transport Scaling -

• Mass Transport \((\omega_e < v_e)\)
  \[
  \frac{\tau_i}{\tau_e} \sim R_{\text{mag}} \sim \left(\frac{v_e}{D_i}\right) \sim T R \sim \left(\frac{I}{R \rho \nu_b}\right)^R
  \]

• Mass Transport \((\omega_e > v_e)\)
  \[
  \frac{V_e t_i}{\Delta} \sim \frac{c}{\omega_{pi}} \quad \text{[Ions carry some current.]}\]

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

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

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

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

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

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

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

\[ Q_{i,j} := Q_i[I, n, r] \]
\[ I = 5 \times 10^3 \hspace{1cm} r = 0.01 \]
\[ I = 5.5 \times 10^4 \hspace{1cm} r = 0.51 \]
\[ n = 3 \times 10^{20} \]

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

(Hydrogen)

\[ Q_i = 15.448 \quad Q_i = 2.3 \times 10^{-10} \]
\[ Q_i = 1.406 \quad Q_i = 0.004 \]

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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

\( \omega_c > \nu \): case

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

Ion Shear Viscosity:

\[ \frac{1}{7} \frac{\nu_{hi}^2}{\nu^2} \frac{\nu_{i}^2}{\omega_{ci}^2} = D_v \]

\( \nu_i = \text{const.} \times m^{-1/2} \)

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

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

\[ \text{then } \mathcal{R}_v = \text{const.} \times \Delta \times V \times \left( \frac{I^2}{\dot{M}} \right)^{1/4} \]
Scaling Issues for MPD Thrusters

\[ RV_{1, j} = \log [RV_{1, i, n, r}] \]

\[ I = 5 \times 10^{-3} \quad r = 0.01 \quad n = 2 \times 10^{20} \]

\[ I = 5.5 \times 10^{-4} \quad r = 0.51 \quad n = 1 \times 10^{10} \]

RV1

MPD

Large Guns

RV1

RV1

0, 0 = 2.964

RV1

0, 10 = 6.107

RV1

10, 0 = 7.13

RV1

10, 10 = 2.277

log \[ R_{visc} \]

20°

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SCALING ISSUES FOR MPD THRUSTERS

— Microscopic Stability —

\[ V_{dr, R} \lesssim v_{thi} \text{ (threshold)} \]

equivalent to

\[ \frac{I^2}{\dot{M}} \lesssim \frac{4e^{-}}{\mu_0} \frac{R}{(c/\omega_p)} v_{thi} \]

If \( (T_i \text{ does not scale with } v^2) \)
Then \( \frac{I^2}{\dot{M}} \lesssim \text{approx. const.} \)

If \( (T_i \text{ scales with } v^2 \text{ [hi } I\text{]}) \)
Then \( \frac{I}{\dot{M}} \lesssim \text{const.} \left[ \text{observed at } hi I \right] \)