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: \( J_r B_\phi \) DRIVES \( \rho v_z \)

**MPD THRUSTERS**

- \( I = \text{few kA} \)
- \( v = 100 \text{ volts} \)
- \( n = 10^{20} \cdot 10^{21} \text{ m}^{-3} \)

**COAXIAL GUNS**

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

Diagram

Visible Emission

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

Diagram

Visible Emission

Intensity Contours (0-255)
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

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 -

\[ \begin{align*}
  C_{\text{time floats}} & \quad P_{\text{time constrained}} \\
  \downarrow u & \quad \uparrow u \\
  \uparrow I_{\text{sp}} & \quad \downarrow
\end{align*} \]

In either case,

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

where \( m_{\text{pr}} = \frac{1}{2} N_{\text{th}} P_0 A_0 f \quad (f = V_0 / V_e) \).

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

- \( I \sim R P \frac{n}{2} \) for fixed \( I_{\text{sp}} \).

\( m_{\text{pr}} \): "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:

\[
\frac{2}{\gamma-1} \frac{dT}{dt} + 2T \nabla \cdot \vec{V} =
\]

= Ohmic Heating + Viscous Heating

- Thermal Conduction Loss

\[
+ n_0 \left\langle \sigma_0 \nu \right\rangle \left[ \frac{1}{2} m_i V^2 - \frac{2}{\gamma-1} T - e_i \right] \]

\[
+ n_\ast \left\langle \sigma_\ast \nu \right\rangle \left[ \frac{1}{2} m_\ast V^2 - \frac{2}{\gamma-1} T - (e_i - e_\ast) \right]
\]

Ionization of excited states:

\[
- \frac{n_0 \left\langle \sigma_0 \nu \right\rangle_{e_\ast}}{n_\ast \left\langle \sigma_\ast \nu \right\rangle_{e_\ast}}
\]

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

H-13
SCALING ISSUES FOR MPD THRUSTERS

- **Transport Scaling** -

  - **Mass Transport** ($\omega_e < \nu_e$)
    \[
    \frac{t_e}{t_i} \sim R_{mag} \sim \left(\frac{v_e \Delta}{D_i}\right) \sim TR \sim \left(\frac{I}{RP^{1/2}}\right) R
    \]

  - **Mass Transport** ($\omega_e > \nu_e$)
    \[
    \frac{v_i \Delta t_i}{A} \sim \frac{c}{\omega_{pi}} \quad \text{[Ions carry some current.]} \]

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

PREDICTIONS FROM “CONVEYOR BELT” MODEL OF ION HEATING (HYDROGEN)

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

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

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

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

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

\[ Q_{i,j} = Q_i[i, n, r] \]

\[ I = 5 \times 10^3 \]

\[ I = 5.5 \times 10^4 \]

\[ r = 0.01 \]

\[ r = 0.51 \]

\[ n = 3 \times 10^{20} \]

\[ Q_i = 15.448 \]

\[ Q_i = 2.3 \times 10^{-10} \]

\[ Q_i = 1.406 \]

\[ Q_i = 0.004 \]

(Hydrogen)
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 — (\( \omega_{ci} > \gamma \): case)

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

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

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

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

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

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

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

- \[ I = 5.10 \]
- \[ r = 0.01 \]
- \[ n = 2.10 \]
- \[ I = 5.5 \times 10^{-4} \]
- \[ r = 0.51 \]
- \[ n = 2 \times 10^{-5} \]

Large Guns

MPD

RV1

RV1 = 2.964
RV1 = 6.107
RV1 = 7.13
RV1 = 2.277

log \( R_{\text{visc}} \)

20°
SCALING ISSUES FOR MPD THRUSTERS

--- Microscopic Stability ---

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

equivalent to

\[ \frac{I^2}{\dot{M}} \lesssim \frac{4\pi}{\mu_0} \frac{R}{c/\omega_p} V_{thi} \]

If (\( T_x \) does not scale with \( V^2 \))

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

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

Then \( \frac{I}{\dot{M}} \lesssim \text{const.} \leftrightarrow [\text{observed at hi I}] \)