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

**MPD THRUSTERS**

![Diagram of MPD Thrusters]

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

**COAXIAL GUNS**

![Diagram of Coaxial Guns]

- $I = 50-100 \text{ kA}$
- $v = \text{few 100 volts - few kV}$
- $n = 10^{20} - 10^{21} \text{ m}^{-3}$
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
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 -

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

In either case,

- \( M_{\text{En}}, M_{\text{Pr}}, M_{\text{Sp}} \) all scale with \( m_{\text{Pr}} \)

where \( m_{\text{Pr}} = \frac{1}{2} N_{\text{th}} S_0 A_0 f \) \( (f = V_0/V_e) \).

Note: \( m_{\text{Pr}} \sim N_{\text{th}} P R^2 \) \( (\text{fixed } A/R) \)

- \( I \sim R P^2 \) 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: $\left( \frac{d}{dt} = \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right)$

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

= Ohmic Heating + Viscous Heating

- Thermal Conduction Loss

\[ + m_o \langle \sigma V \rangle_o \left[ \frac{1}{2} m \dot{\vec{v}} \vec{v}^2 - \frac{2}{\gamma-1} T - e_i \right] \]

\[ + m \langle \sigma V \rangle \left[ \frac{1}{2} m \dot{\vec{v}} \vec{v}^2 - \frac{2}{\gamma-1} T - (e_i - e*) \right] \]

ionization of excited states:

\[ - \frac{m_o \langle \sigma V \rangle_o}{m \langle \sigma V \rangle} e* \]

where $\frac{1}{2} m \dot{\vec{v}} \vec{v}^2$ means $\frac{1}{2} m \dot{\vec{v}} \left( \vec{v} - \vec{v}_m \right)^2$. 

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SCALING ISSUES FOR MPD THRUSTERS

- Transport Scaling -

- Mass Transport ($\omega_c < v_e$)
  \[ \frac{t_e}{t_i} \sim R_{mag} \sim \left( \frac{V_e A}{D_2} \right) \sim \frac{T}{R} \sim \left( \frac{I}{RP^{1/2}} \right) R \]

- Mass Transport ($\omega_c > v_e$)
  \[ \frac{V_t t_i}{\Delta} \sim \frac{c}{\omega_{pi}} \]
  [Ions carry some current.]

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

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

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

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

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

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

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

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

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

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

\[ r = 0.01 \]

\[ r = 0.51 \]

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

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

(Hydrogen)

\[ Q_{0,0} = 15.448 \]

\[ Q_{0,10} = 2.3 \cdot 10^{-10} \]

\[ Q_{10,0} = 1.406 \]

\[ Q_{10,10} = 0.004 \]
SCALING ISSUES FOR MPD THRUSTERS

- Macroscopic Stability -

The viscous Reynolds number (with magnetized ions) may become large and may thereby induce turbulent channel flow.
Viscous Reynolds number: \( \frac{V \Delta}{D_v} = R_v \)

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

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

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

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

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

$$RV1_{1,j} = \log(10) \left[ RV1_{1,1} \right]$$

$$I = 5 \times 10^3$$
$$r = 0.01$$
$$n = 2 \times 10^2$$

$$I = 5.5 \times 10^4$$
$$r = 0.51$$
$$n = 2.10$$

Large Guns

MPD

$$RV1_{0,0} = 2.964$$

$$RV1_{10,0} = 7.13$$

$$RV1_{0,10} = 6.107$$

$$RV1_{10,10} = 2.277$$

$$20^\circ$$

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SCALING ISSUES FOR MPD THRUSTERS

— Microscopic Stability —

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

Equivalent to

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

If \((T_{\theta} \text{ does not scale with } V^2)\)

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

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

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