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LOS ALAMOS RESEARCH IN NOZZLE BASED COAXIAL PLASMA THRUSTERS

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COAXIAL THRUSTER RESEARCH

Outline

- Research Approach
- Perspectives on efficient MPD operation
- NASA and DOE supported research
  - Ideal MHD plasma acceleration and flow
  - Electrode phenomena
  - Magnetic nozzles
- Future research directions and plans

COAXIAL THRUSTER RESEARCH

Collaborators and Contributors

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COAXIAL THRUSTER RESEARCH

Research Approach

NEAR TERM FOCUS:

- Apply coaxial plasma gun research experience to optimizing thruster efficiency and specific impulse
- Ascertain scaling properties in terms of size and power
- Investigate performance and thruster design at power levels and sizes applicable to "near term" missions like orbital transfer
  - In steady-state
  - For adjustable duty-cycle (pulsed)
- Apply insights to the design of more efficient MPD thrusters

LONGER TERM FOCUS:

- Pursue MMWe coaxial thruster optimization for farther term propulsion missions and other applications

Efficient MPD Operation

Perspectives

In addition to frozen flow losses, efficiency is limited by two processes:

- Macro plasma acceleration and detachment
  - Efficient operation ⇒ High grade plasma
  - High grade plasma ⇒ Ideal MHD
  - Ideal MHD ⇒ Economy of scale
- Electrode phenomena
  - Electrode fall losses are strongly coupled to magnetic configuration

These processes are coupled by the Electrical Effort (Morozov Hall parameter) *

$$\Xi \equiv \left(\frac{m_i}{e}\right)\frac{I}{\dot{M}} \approx \left(\frac{c}{\omega_{pi}}\right)\frac{1}{\Delta}$$

* Schoenberg, et al., AIAA 91-3770 (1990)

EFFICIENT MPD OPERATION

Perspectives (continued)

- Good MHD performance drives $\Xi << 1$ (relevant to ion acceleration losses)
- Minimization of electrode phenomena also drives $\Xi << 1$ (relevant to electrode losses)
- Plasma stability considerations places bounds on Ξ
  - Upper bound set by Lower Hybrid Drift Instability
  - Lower bound set by beta limits (Raleigh-Taylor, Kelvin-Helmholtz) in high grade plasma systems

These perspectives lead to an optimization approach

EFFICIENT OPERATION AND CONTROL

Magnetic Nozzle

Dominance of MHD leads to the efficacious use of magnetic nozzles for optimization of:

- Macro plasma acceleration and detachment
- Electrode phenomena
- Plasma stability

NASA and DOE SUPPORTED RESEARCH

Unoptimized "As-was" Experiments

- Power range 10-40 MW
- Unoptimized gun
- Unoptimized 2.5 MJ capacitor bank
  - 1 ms, round-top discharges
- Unoptimized $B_{r,z}$ (nozzle) field
  - Applied field coil in center electrode (cathode)
- Wide range of diagnostics
  - Multi-chord interferometry
  - Temporally and spatially resolved bolometry
  - Langmuir and magnetic probes
  - Temporally and spatially resolved IR calorimetry
  - Neutral particle spectroscopy

NASA and DOE SUPPORTED RESEARCH

Plasma Acceleration and Flow

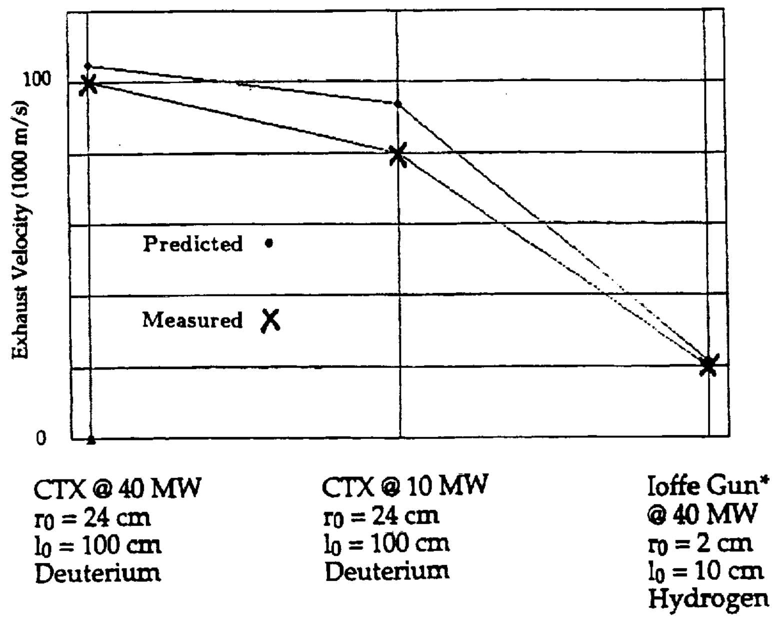
Previous work has derived parametric expressions for plasma acceleration, flow, and detachment*

- Experiments have shown that plasma flow is accelerated to the magnetosonic velocity in agreement with theory
- High grade plasma observed
  - Magnetic Reynolds number ≈ 1000
  - $\Xi < 0.5$
- Coaxial gun research shows remarkable agreement between MHD flow predictions and experiment over a wide range of size and power

* Gerwin, et al., AFOSR Report AL-TR-89-092, (1990),

Schoenberg, et al., AIAA 91-3770 (1990), and

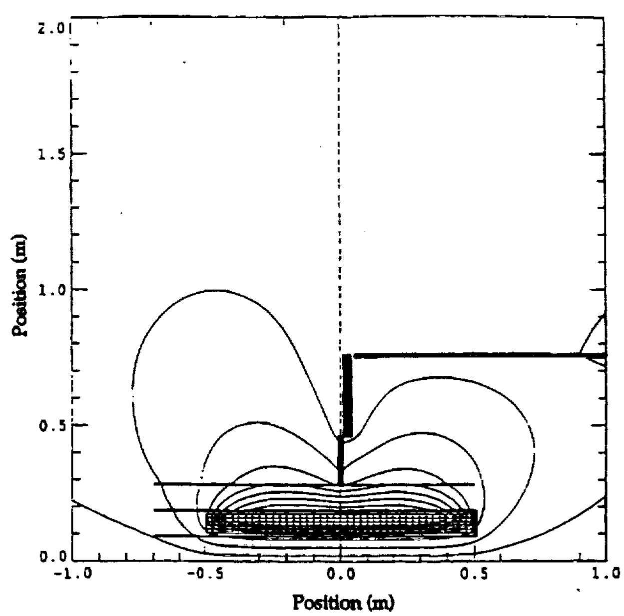
Moses, et al., Proceedings of 9th Symposium on Space Nuclear Power Systems (1992).



* Afanas'ev et al., Sov. Phys. Tech. Phys., 36, 505 (1991)

NASA AND DOE SUPPORTED RESEARCH

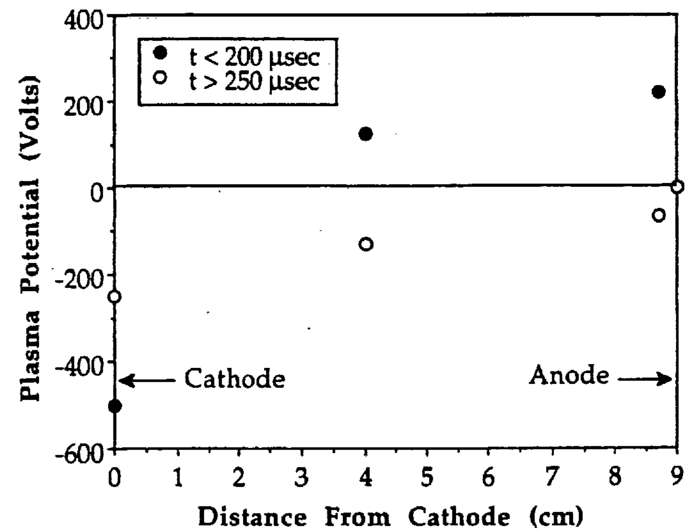
Electrode Phenomena



- Calculation of vacuum field at time of shot
- Field lines connect anode to cathode
- Field lines distort due to plasma flow

ANODE FALL

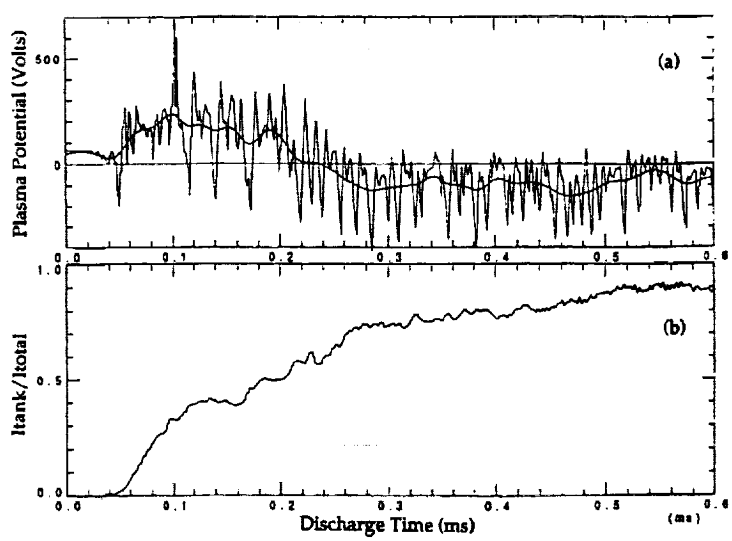
Plasma Potential Measurements



- 40 MW shots
- Floating Langmuir probe measurements
- Anode fall reversed for t < 200 μs

ANODE FALL

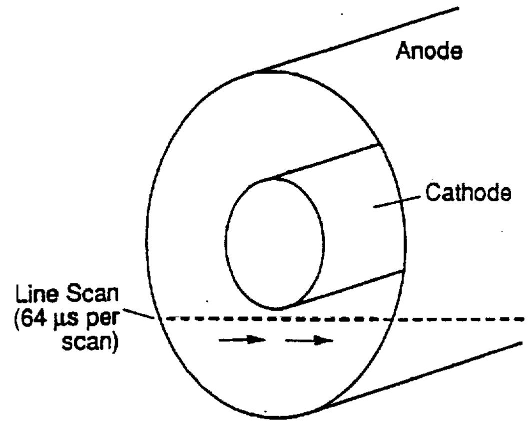
Evolution of Magnetic Field Structure



- Field lines connect cathode to anode at early times
- As discharge evolves, plasma stretches field lines thereby connecting cathode to tank wall

INFRARED ELECTRODE CALORIMETRY

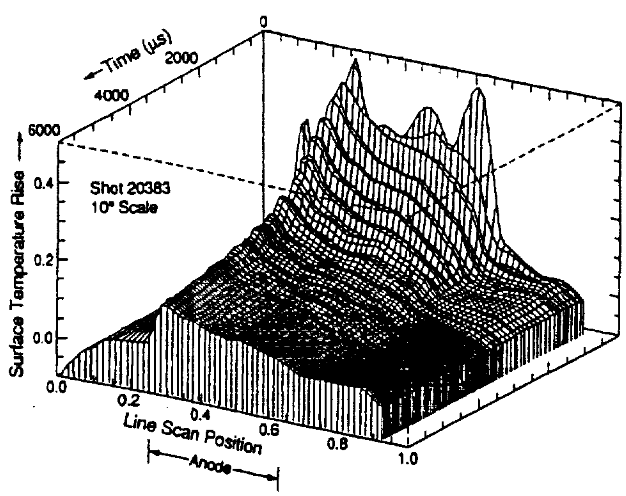
Experimental Setup



- Infrared video camera in line scan mode used to measure electrode temperature
- Temperature rise converted to energy flux

INFRARED ELECTRODE CALORIMETRY

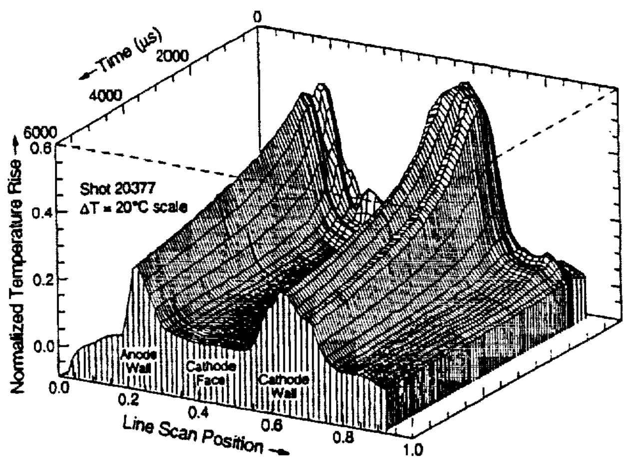
Results for 15 MW Shot



- Energy flux ≈ 13 MW/m^2 deposited on anode for 15 MW shot

INFRARED ELECTRODE CALORIMETRY

Results for 40 MW Shot



- Energy flux ≈ 30 MW/m^2 deposited on anode for 40 MW shot

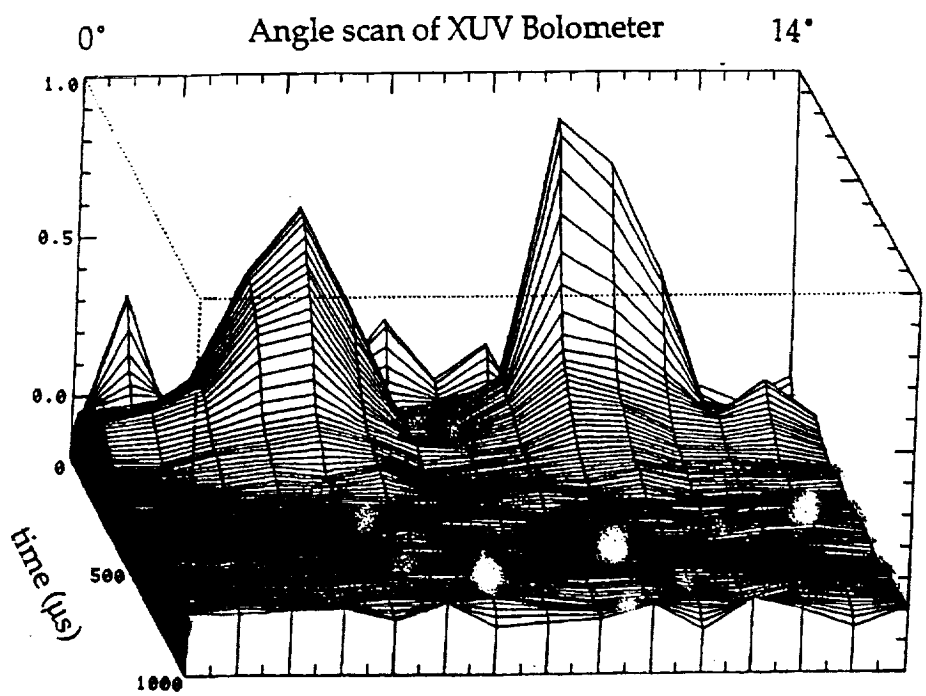
INFRARED ELECTRODE CALORIMETRY

Interpretation of Results

A comparison of measured energy flux to that predicted by the anode fall data has been made.

- For 40 MW discharge $P_{anode} \approx \Gamma_{thi} \times 200$ eV = 40 MW/m^2
- Reasonable agreement with IR data

BOLOMETRY



- XUV photodiode used to measure absolute radiation losses *
- Radiative power loss of 3-6% for 10-40 MW shots

* Maqueda and Wurden, to be published in Rev. Sci. Inst.

ELECTRODE PHENOMENA

Conclusions

- Magnetic configuration can affect/control anode fall
- Temporally and spatially resolved electrode calorimetry in reasonable agreement with power loss to anode from ion flux
- Radiative losses small (less than 10%)
- Global power balance estimates in progress

COAXIAL THRUSTER RESEARCH

Future Research Directions and Plans

- New facility design for 10 MW, 10 ms, flat-top (quasi-steady state) operation with mass flow control
- Electrically isolate anode from tank wall
- Repeat electrode loss, plasma flow, power balance, and spatial magnetic field measurements on unoptimized gun under quasi-steady-state operation
- Theory/modeling support to evolve capabilities
- Design and test of an optimized gun with new magnetic nozzle
- Apply research conclusions to MPD thruster design