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LOS ALAMOS RESEARCH IN NOZZLE BASED COAXIAL PLASMA THRUSTERS

Kurt F. Schoenberg

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Colleagues and Collaborators

- Richard Gerwin
- Robin Gribble
- Ivars Henins
- John Marshall
- Ron Moses
- Jay Scheuer
- Glen Wurden
- Dorwin Black, N.C. State
- Rob Hoyt, U. Washington
- Tom Jarboe, U. Washington
- Robert Mayo, N.C. State

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Outline

- Colleagues and Contributors
- History: Where we're coming from
- Our Perspectives on High-Performance EP
- Approach
- On Going Research Activities
- Plans

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Historical Perspective

Los Alamos has conducted continuous research in coaxial plasma accelerators since their inception.

- Pioneered by John Marshall in the late 50's
- A rich history of applications:
  - Propulsion (1960's)
  - Plasma Fueling (1960's)
  - Radiation Source (1960's)
  - Space Plasma Injection (Birdseed) (1970's)
  - Magnetic Fusion Research (1980's)
  - SDI Research (1980's)
  - Propulsion (in collaboration with NASA LeRC) (1990's)
  - Materials Processing (1990's)
- Recent focus on steady-state operation (pioneered by Morozov)

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Approach

Can electrodynamic-based thrusters achieve the performance required for space missions of interest?

- **Optimize** large-scale, multi-megawatt electrodyamic thruster performance.
- **Ascertain** performance scaling in terms of size and power.
- **Engineer** performance at power levels applicable to NASA or DOD "near term" missions like orbital transfer or robotic exploration.
  - In steady-state
  - For adjustable duty-cycle (pulsed) operation

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Approach

Why Study Large, High Power Devices?

- There is a minimum "buy-in" for high performance operation!
- How high and how large is under investigation.
- Pulsed operation may be our "evolutionary approach".

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

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)

MMWe ELECTRIC PROPULSION

Efficacy of Magnetic Nozzles

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

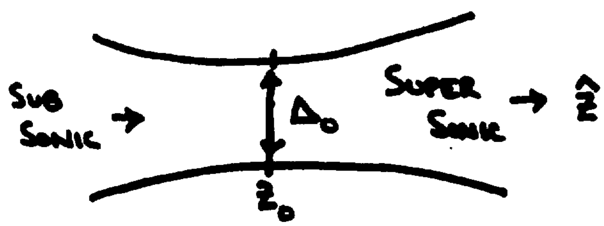
- Acceleration
- Detachment
- Electrode Phenomena

Magnetic nozzle expansion ratios are an important efficiency optimizer

MMWe THRUSTER DEVELOPMENT

Magnetic Nozzles

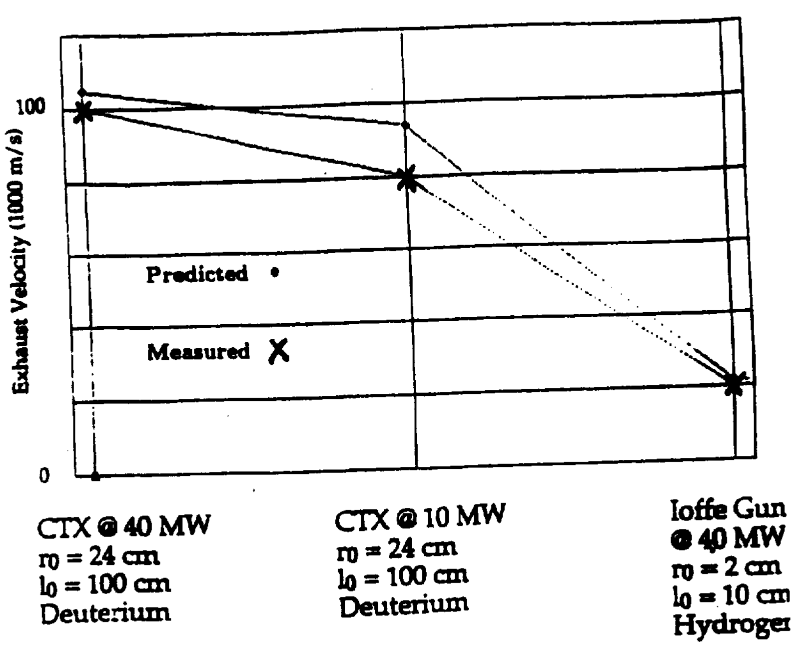
- Plasma Acceleration in Ideal MHD Requires ($\nabla \times \mathbf{V} \times \mathbf{B} = 0$):
  - Non-ideal effects
  - Converging-Diverging Flow (Nozzle)
- Hydrodynamic Nozzle Theory has Direct Analogs in MHD (Morozov):



Mach 1 $\equiv$ Magnetosonic Velocity $= \sqrt{C_{so}^2 + C_{Ao}^2}$

COAXIAL THRUSTER PERFORMANCE

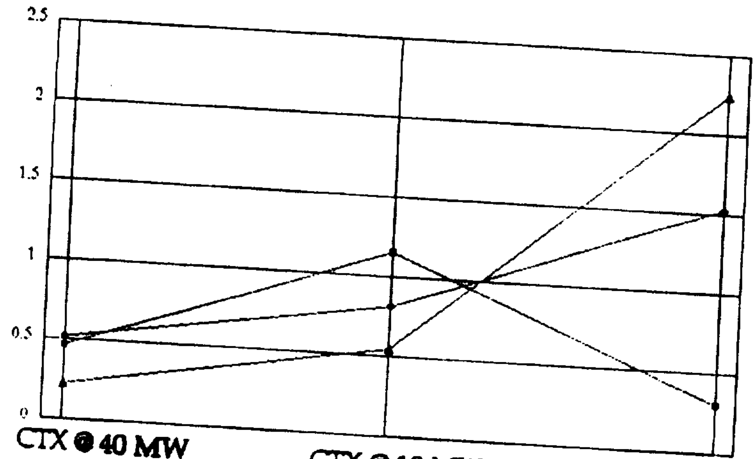
Exhaust Velocity



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

COAXIAL THRUSTER PERFORMANCE

Electrical Effort



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

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FY91 & FY92 As-Was Experiments

- Power range 10-40 MW
- Unoptimized Gun
- Unoptimized 2.5 MJ capacitor bank
  - 1ms, round-top discharges
- Unoptimized $B_{r,z}$ nozzle field
- Wide range of diagnostics
  - Mullti-chord interferometry
  - Temporally and spatially resolved bolometry
  - Temporally and spatially resolved IR calorimetry
  - Langmuir and magnetic probes
  - Neutral particle spectroscopy

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FY91 & FY92 As-Was Experimental Conclusions

- High exhaust velocity achieved (10^5 m/s) in agreement with MHD based theory.
- Thruster operational impedance in agreement with MHD based theory for constant $I^2/\dot{M}$.
- Radiative (frozen flow) losses small ($\leq 10\%$)
- Applied magnetic configuration can affect and control the anode fall.
- Power flux to the electrodes well quantified.
- Power flux to the anode probably dominated by ion flux
- Global electrode power loss probably less than 50 % at high power operation (40 MW).

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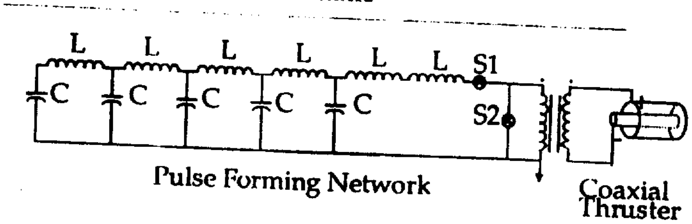
FY93 Optimized Experiments

In FY92, CTX was converted into a "world-class" high power MPD test facility

- PFN controlled 2 MJ, transformer coupled capacitor bank
- 10 ms flat-top discharges at 1 to 50 MW (10 - 100 kA and 50 to 1000 v)
- Constant propellant injection at 1 to 10 g/s (deuterium)
- DC control of applied nozzle field
- Electrically isolated test-stand
- PC / Sparc Station control, data acquisition. and analysis
- Full diagnostics capability

Pulse Forming Network

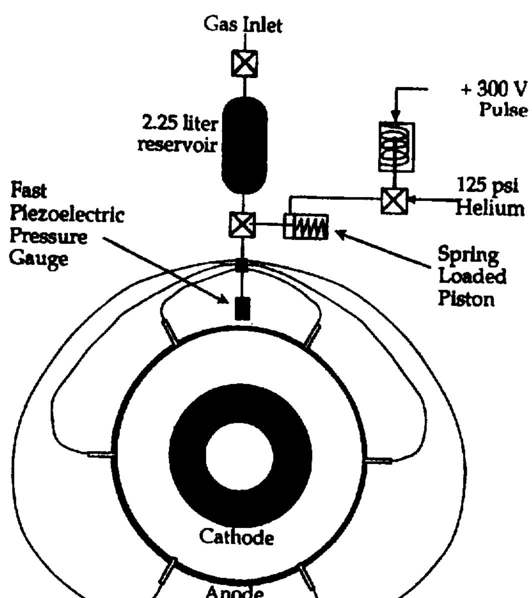
Schematic



- C = 0.8 mF
- L = 0.125 mH
- 5:1 Transformer
- 2.0 MJ Stored Energy
- 10 ms Flat Top Pulse

Long Pulse Gas Valve System

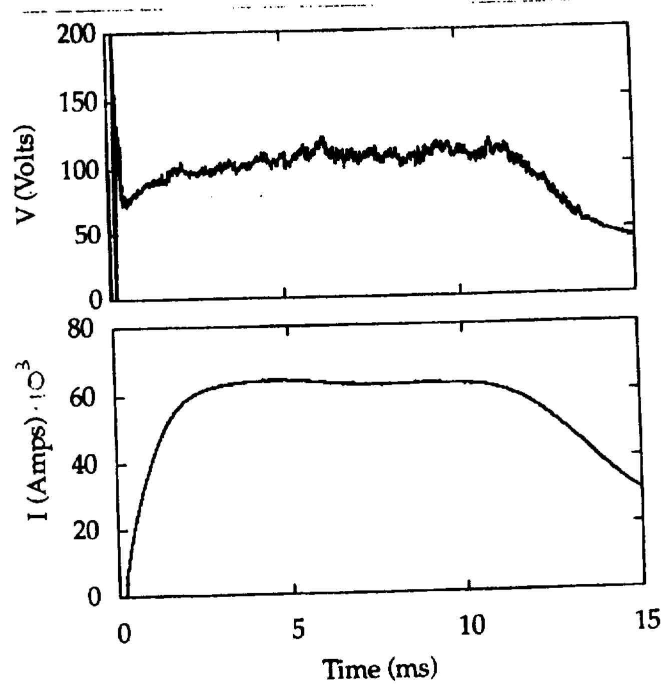
Schematic



- Stainless steel feed lines are of equal length

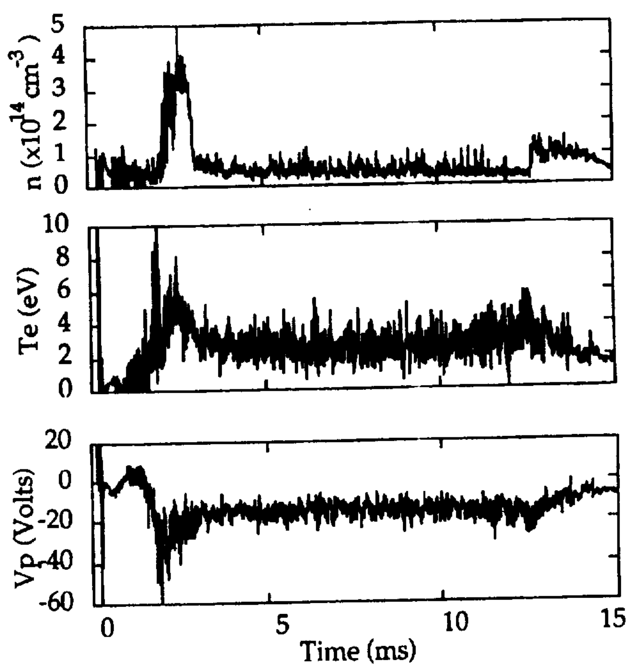
Thruster Current and Voltage

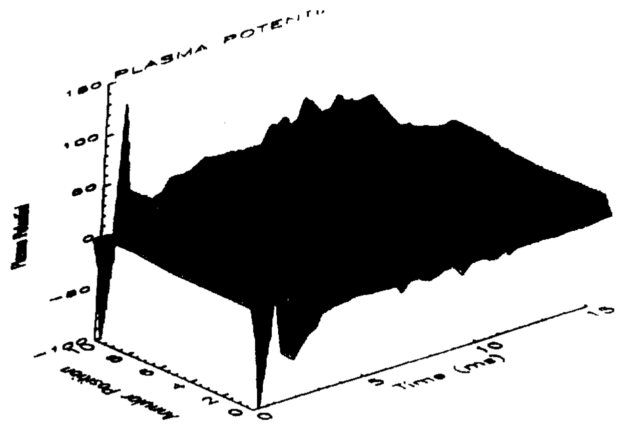
6 g/s helium

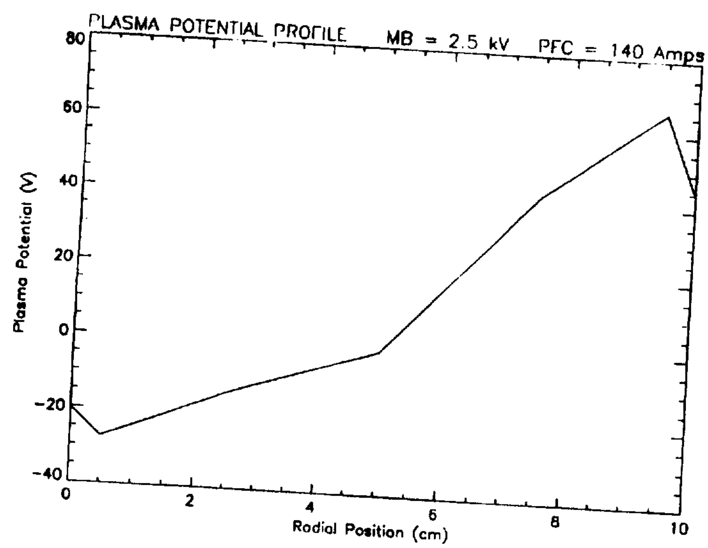


Triple Langmuir Probe Data

5.4 cm inside exit plane

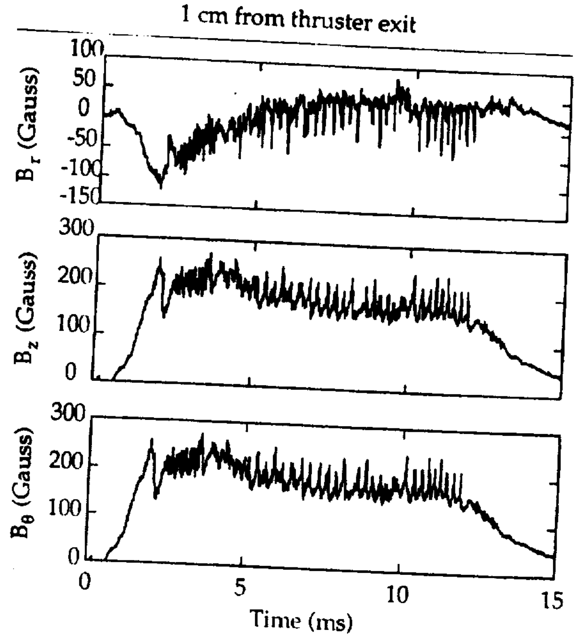


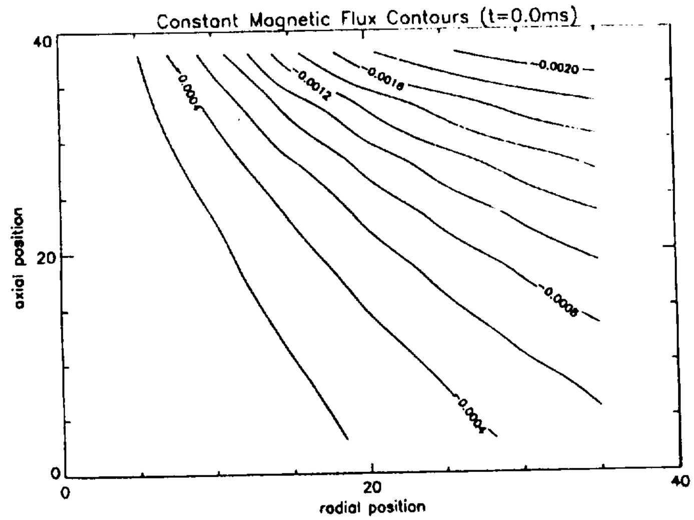


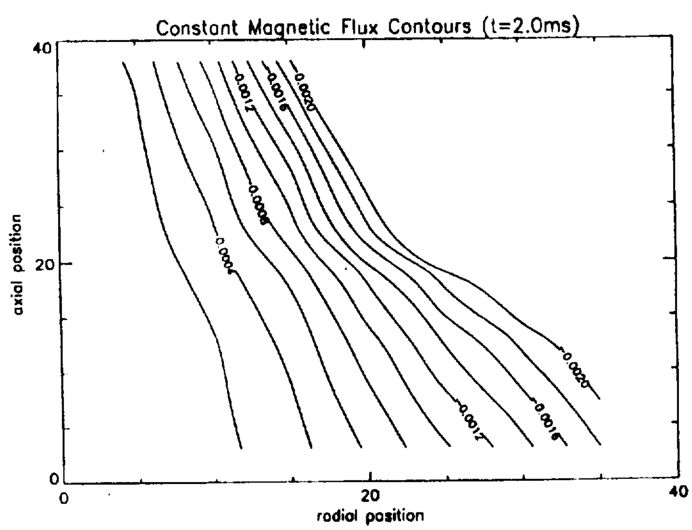


Magnetic Field Fluctuations

1 cm from thruster exit




Constant Magnetic Flux Contours (t=0.0ms)
axial position
radial position
0
20
40
0
20
40
0.0020
0.0016
0.0012
0.0008
0.0004


Constant Magnetic Flux Contours (t=2.0ms)
axial position
radial position
0
20
40
0
20
40
0.0020
0.0016
0.0012
0.0008
0.0004

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Plans

- With quasi-steady-state capabilities:
  - Experiments to repeat electrode loss, plasma flow, power balance, and spatial magnetic field measurements on the unoptimized coaxial gun.
  - Control of anode fall by applied field.
  - Estimate of thruster efficiency through power balance.
- Design and construct an optimized applied field thruster.
- Repeat performance assessment.
- Apply research conclusions to MPD thruster design.

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Concluding Remarks

Will the National Labs be advancing the state-of-the-art in electric propulsion in FY 94?