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REVIEW OF RECENT WORK ON MPD THRUSTERS AT MIT

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Outline

* Basic Philosophy of MIT SPPL work
* 2-d numerical MPD simulations: E. Niewood; Ph.D
* Analysis of MPD boundary layers; J.M Chanty; Ph.D
* Ignition of MPD thrusters; E. Sheppard; Ph.D

Basic Philosophy

* Develop a basic research program to consider some of the underlying physics issues associated with MPD thrusters
  - Complete analysis of classical 2-d flow inc. Hall effect, viscosity, ion slip etc..
  - Correct appreciation for the boundary conditions associated with the various types of boundary layers
  - Understand the ignition process in an MPD thruster

MPD Simulations

A good numerical simulation would be useful to help:

- determine important physical effects
- predict performance
- determine plasma parameters at many locations
- design better thrusters

Existing Multidimensional Simulations

- Sleziona et. al at IRS. - Axisymmetric simulation with non-equilibrium temperature and frozen or equilibrium ionization.
- LaPointe at NASA Lewis - Axisymmetric one fluid simulation with fluid transport. Complex geometries.
- Caldo et. al at Princeton - Axisymmetric simulation with thermal and ionizational non-equilibrium. Inviscid. Includes anomalous transport.

Previous SPPL Modeling

- Numerical axi, MHD simulation - Chanty, 1987
- Analytical 1-d, 1-fluid solution - Martinez 1987,1992
- Numerical 1-d, 2-fluid simulation- Niewood 1989,1991
- Numerical 2-d, 2-fluid simulation- Niewood 1991
- Numerical 2-d, 2-fluid simulation- Miller 1991
- Numerical axi, 2-fluid simulation- Niewood 1991

Present Focus

Recent and current modeling focuses on desire to

- include as much of relevant physics as possible
- obtain solutions at high power and in electromagnetic regime
- determine importance of Hall effect, particularly with regard to starvation and anode voltage drops.

Status At Last Meeting

Two dimensional two fluid simulation developed including:

- Non-equilibrium ionization.
- Thermal non-equilibrium.
- Electron heat conduction.

Near anode voltage drops shown to be similar to those observed experimentally.

Progress

Additions to model include:

- Axisymmetric formulation.
- New ionization model. Old Hinnov- Hirschberg model overpredicted ionization and recombination. New model based on examination of detailed kinetics by Sheppard.
- Other cylindrical geometries.

Progress

- Neutral slip. Separate momentum equations in each direction for ions and neutrals. Collisional drag between species couples velocities.
- Catalytic wall boundary conditions. All ions which reach the wall return to the plasma as neutrals.

Progress

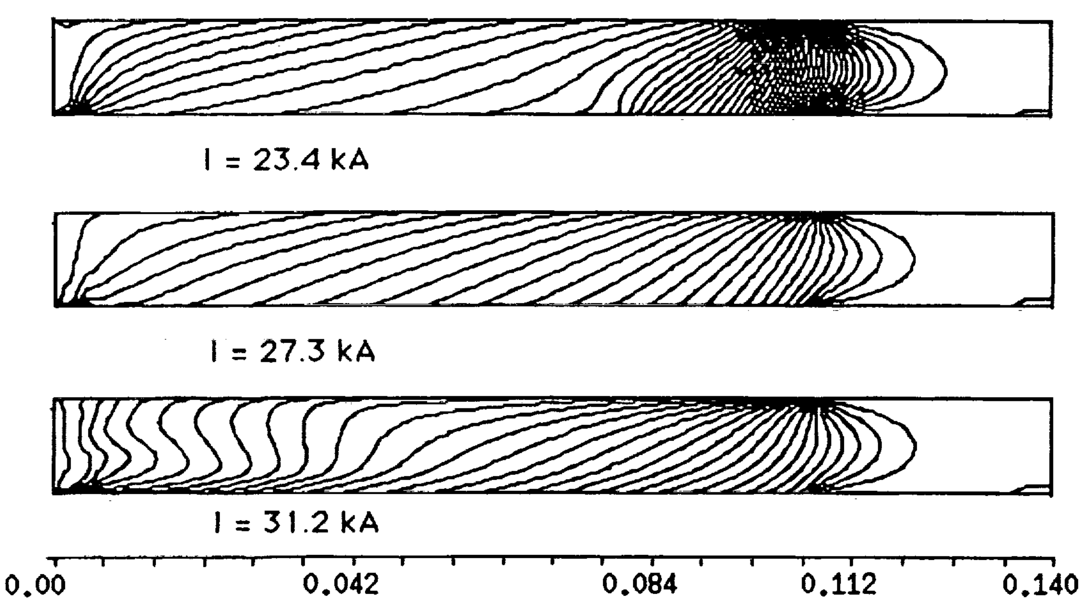
- New viscosity model. Must include substantial slip. Based on work by Fernandez and Fernandez.(Physics of Fluids, July 1987)
- Heavy species heat conduction.
- Magnified anode layer. Simpler model is solved between last interior point of simulation and boundary to give anode boundary conditions.

Results: Different Cases

Four cases under examination.

- Case 1 - Thruster length = 0.14m, electrode length = 0.1m, interelectrode gap = 0.02 m, cathode outer radius = 0.052 m, mass flow = 4 g/s, current = 23.4 kA. Converged solution obtained.
- Case 2 - Same as Case 1 with current = 27.3kA. Stable solution obtained, converging.
- Case 3 - Same as Case 1 with current = 31.2 kA. Solution is stable, but oscillating, not converging.
- Case 4 - Thruster length = 0.1m, electrode length = 7.6cm, interelectrode gap = 1.6 cm, cathode outer radius = 0.48cm, mass flow = 1 g/s, current = 3.4kA. Solution stable, converging?

Results: Current Contours



Results: Voltage and Voltage Drops

Case 1: I = 23.4 kA, Vtot = 8.1V, Vanode ~ 0

Case 2: I = 27.3 kA, Vtot = 14.6 V, Vanode ~ 2.6 V

Case 3: I = 31.2 kA, Vtot = 33 V, Vanode ~ 18 V

Case 4: I = 3.4 kA, Vtot ~ 6 V, Vanode < 0

Results: General

- Hall effect leads to skewing of the current lines and substantial starvation of the near anode region.
- These effects in turn could be responsible for the large anode voltage drops observed experimentally.
- A better understanding of starvation, its causes, and its effects could lead to significantly improved efficiency for MPD thrusters.

Results: General

- Anode starvation could cause extreme sensitivity to small tank back pressures.
- Anode injection, or some other technique to reduce starvation, could lead to substantially improved efficiency.
- Slip leads to low electrode ionization fractions.
- Slip may lead to cathode fall voltages.

Future Work

- Get more converged solutions.
- Model more complex thruster geometries.
- Obtain better understanding of voltage drops.
- Include anomalous transport.
- Include second ionization.
- Determine ways to increase efficiency.

VI: Formulation

- Mass Conservation

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

- Momentum Conservation

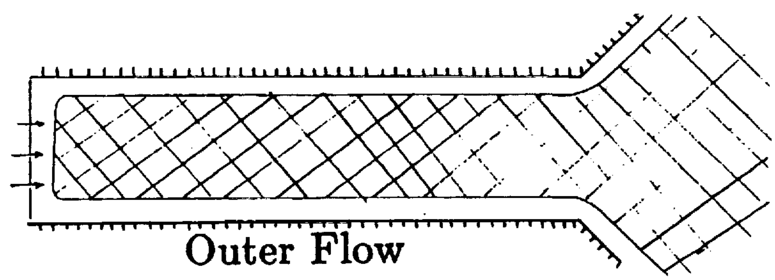
$$\rho \ (\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla(p + b^2) = 0$$

- Energy Conservation

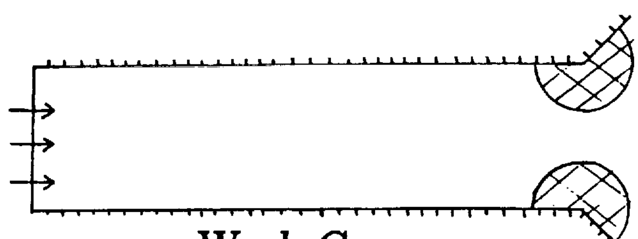
$$\frac{1}{\gamma - 1}\rho^{\gamma} \ (\mathbf{u} \cdot \nabla) \left(\frac{p}{\rho^{\gamma}}\right) = \frac{2}{Rm}(\nabla b)^2$$

- Magnetic Field Convection

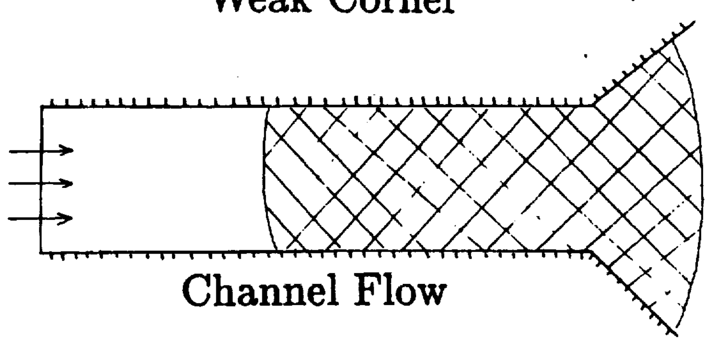
$$\rho \ (\mathbf{u} \cdot \nabla) \left(\frac{b}{\rho}\right) = \frac{1}{Rm}\nabla^2 b$$



Outer Flow



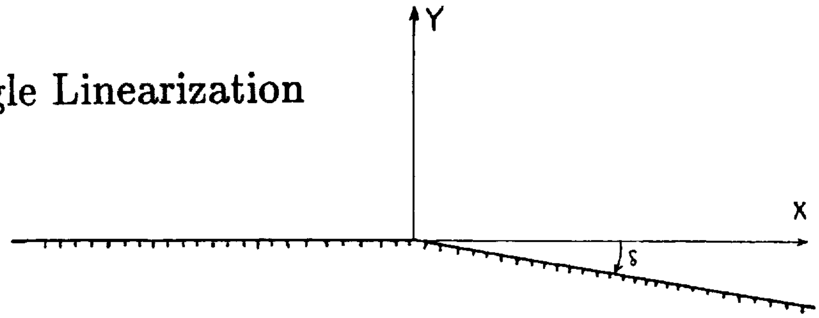
Weak Corner



Channel Flow

XII. Weak Corner: Resistive Plasma Model

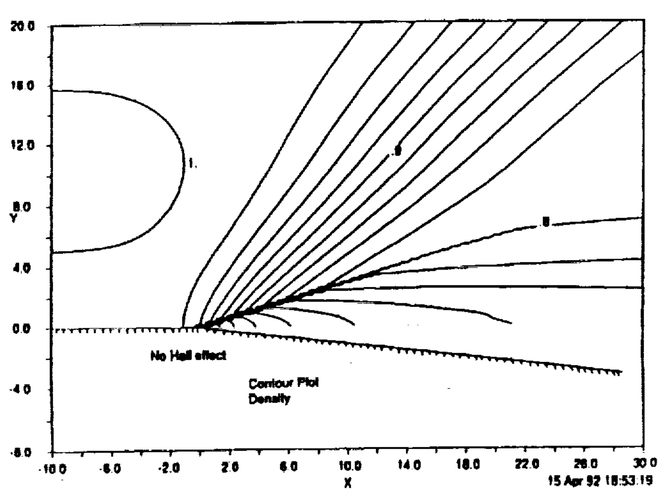
- Small Angle Linearization

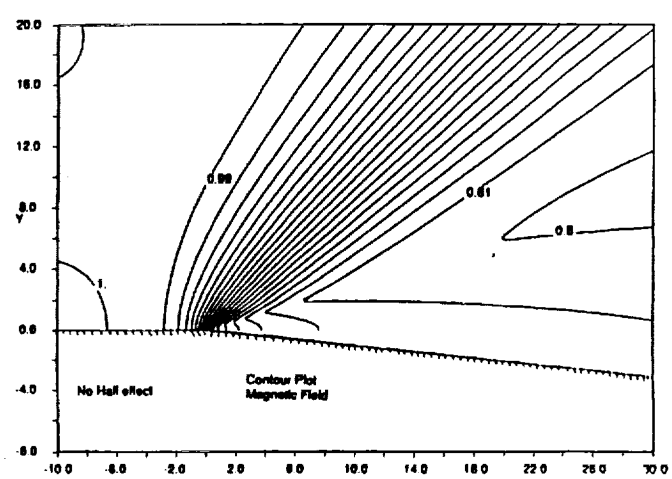


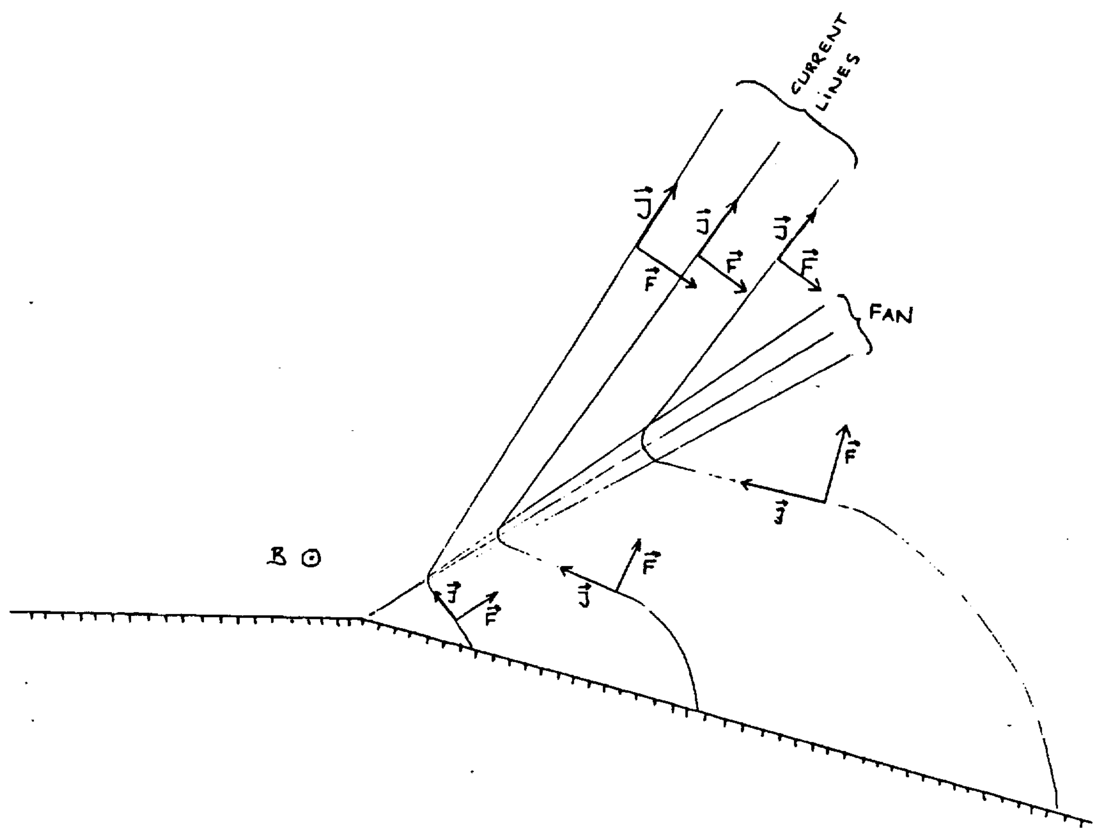
- 4-th Order Linear Operator

$$\left\{\frac{\partial}{\partial X}\left((1-M_v^2)\frac{\partial^2}{\partial X^2}+\frac{\partial^2}{\partial Y^2}\right)-\frac{M_v^2}{M_a^2}\left((1-M_a^2)\frac{\partial^2}{\partial X^2}+\frac{\partial^2}{\partial Y^2}\right)\nabla^2\right\}v_1=0$$

- Properties: $M_v > 1$, Hyperbolic and Elliptic
- Solution: Fourier Transformation along X, Transfer of Boundary Conditions

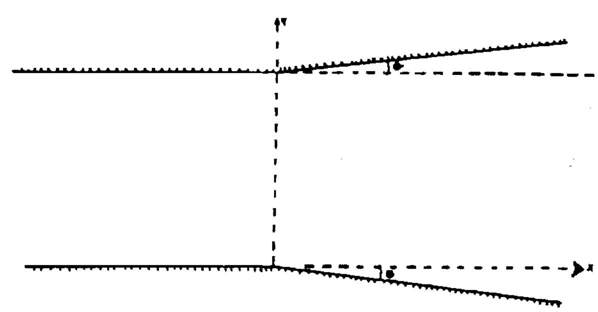




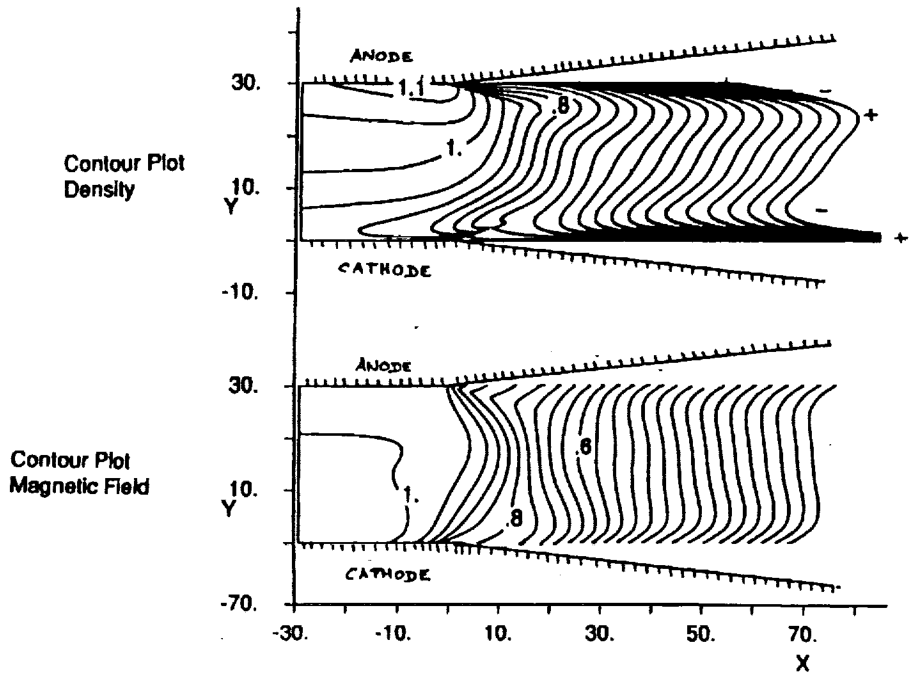


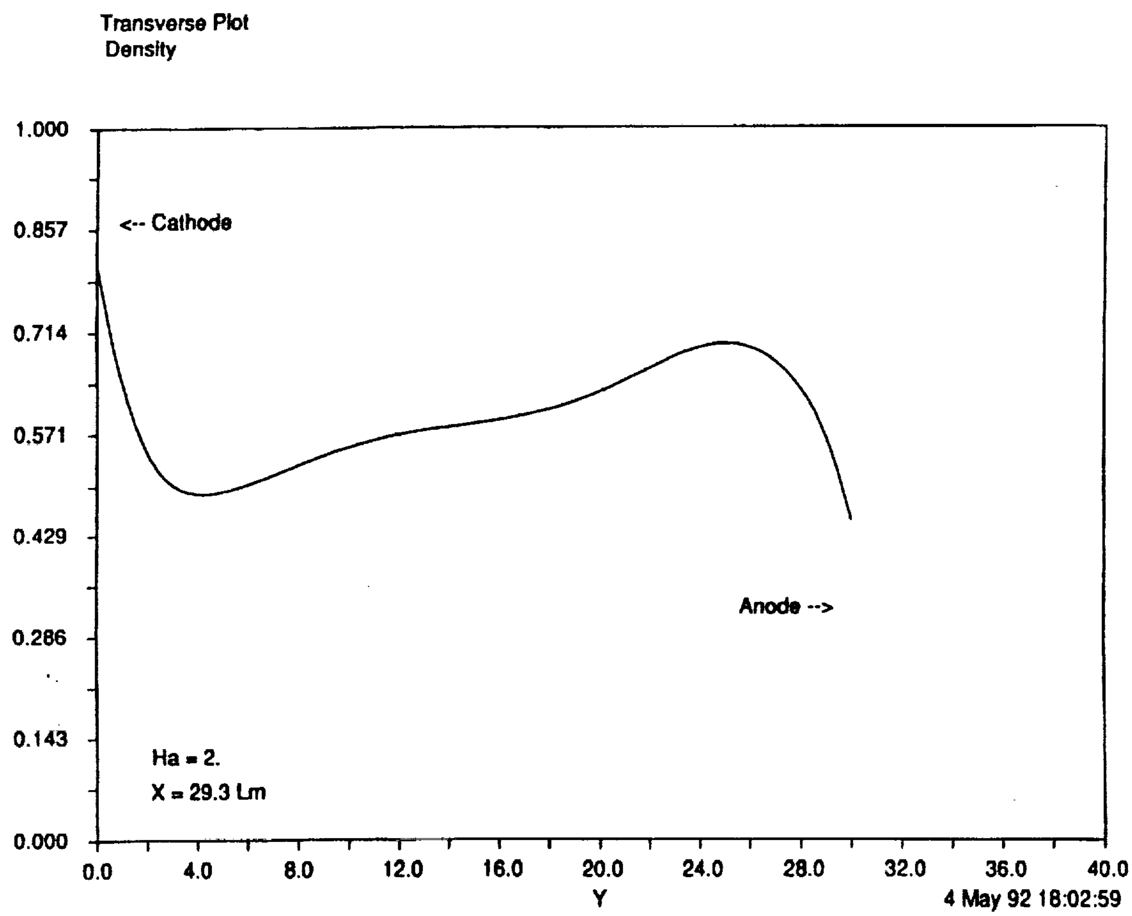
XIV. Channel Flow: Problem Definition

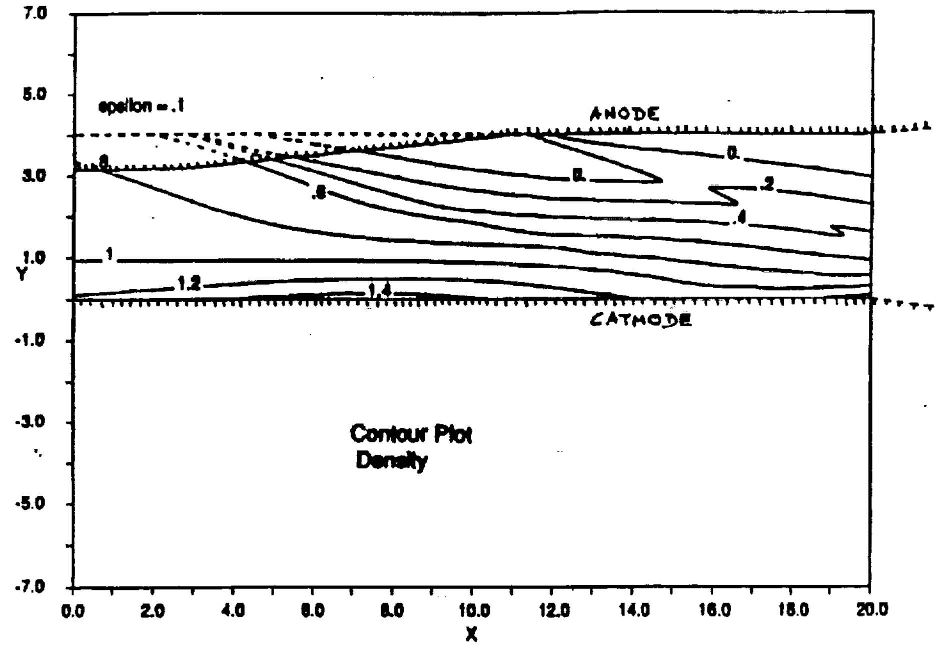
- Geometry

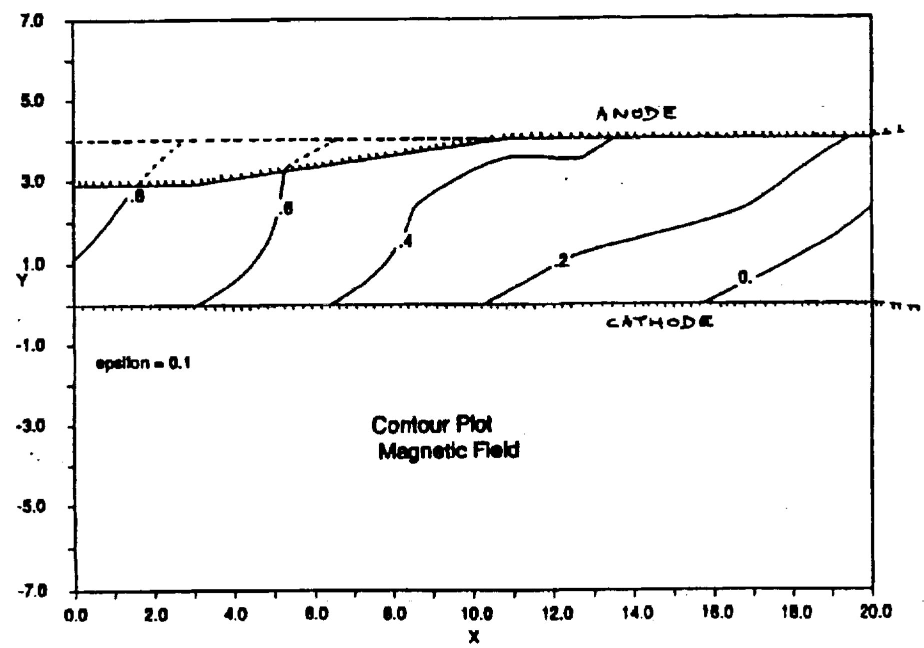


- Formulation: Analogous to Weak Corner
- Incoming Flow: $M_V > 1$
- Include Hall Conductivity


Contour Plot
Density
Contour Plot
Magnetic Field
ANODE
CATHODE
ANODE
CATHODE
1.1
1.
.8
.6
1.
.8
+
-
30.
10.
-10.
30.
10.
-70.
Y
Y
-30.
-10.
10.
30.
50.
70.
X


Transverse Plot
Density
1.000
0.857
0.714
0.571
0.429
0.286
0.143
0.000
<-- Cathode
Anode -->
Ha = 2.
X = 29.3 Lm
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
Y
4 May 92 18:02:59





XV. Linearized Channel Flow: Discussion

- Effect of Hall Conductivity
  - mass depletion, boundary layers
- Effect of Channel Height
  - large channel: one-dimensional model valid
  - narrow channel: expansion starts upstream of the exit

Nonequilibrium Ionization Work

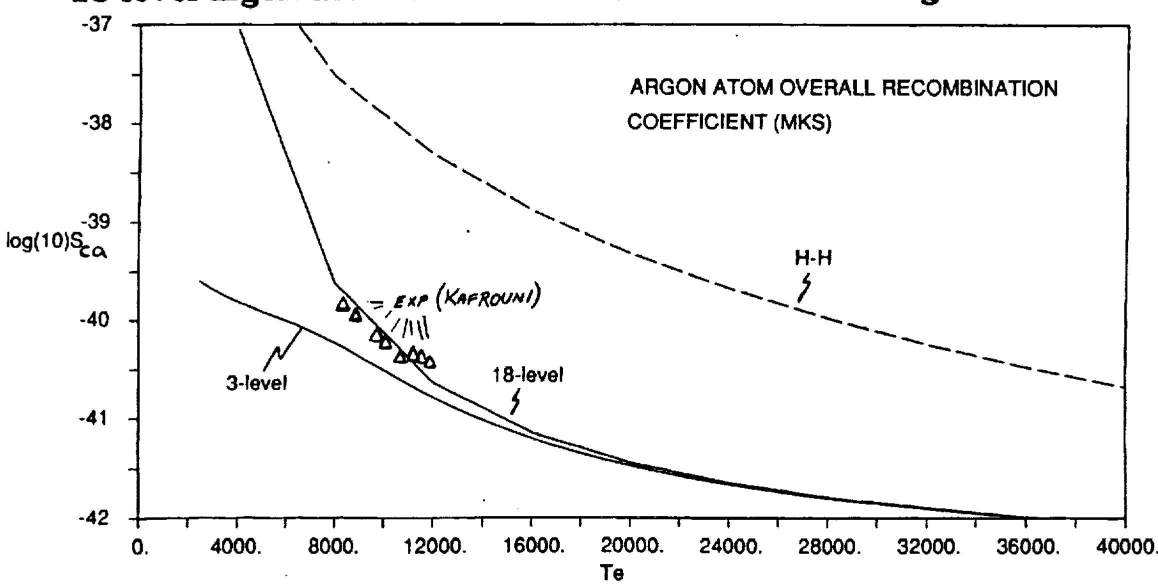
* Model atoms (A,H) and ions (A) as sets of excited states, and use a Bates-Kingston-McWhirter model for volumetric production rates for each state. (includes collisional and radiative processes)

* Calculate the excited state populations and overall collisional rate coefficients (assuming dynamic equilibrium of the excited states and neglecting radiation).

* Apply these rate models to the problem of steady-state inlet ionization in MPD thrusters.

Nonequilibrium Ionization

Assuming the excited states are in dynamic equilibrium, and neglecting radiation, overall ionization and recombination coefficients are calculated. Shown here are results from three and 18 level argon atomic models and Hinnov-Hirschberg as reference:



Inlet Ionization

* Consider the problem of steady-state, self-sustained initiation of ionization in a propellant injected into an MPD thruster. (the gas/plasma transition)

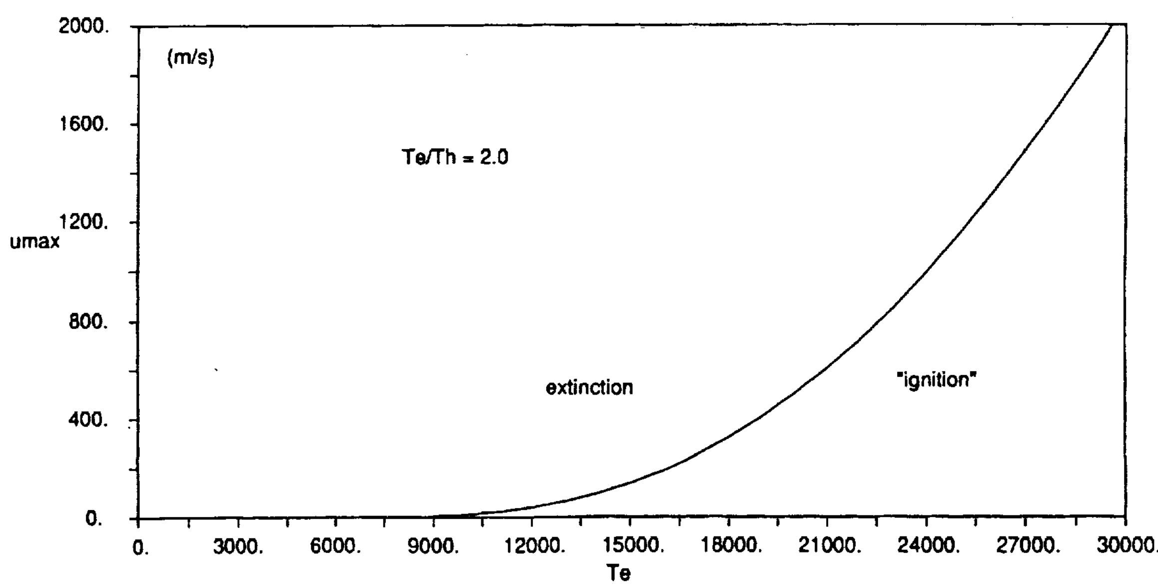
* Hypothesize that this "ignition" occurs due to a combination of back diffusion of electron-ion pairs and radiation from the downstream plasma.

* Ionization via electron-atom collisions may be one-step (direct ionization) or multi-step (through the excited states).

* Radiation may also be one-step or multi-step.

Inlet Ionization

For "ignition" in a finite length in a collisions-only 1-d the ionization mfp must be smaller than the axial back-diffusion scale length. This imposes a limit on the injection speed:



Inlet Ionization

Current and Future Work:

* Consider in detail the roles of temperature variation and the rapid acceleration near the inlet of an MPD thruster in the ignition process.

* Look into the roles of the individual excited states (modelled as lumped levels):

  - Under what conditions will the excited states be out of dynamic equilibrium? (low Te, ne) What is the effect on ignition?

  - What is the influence of radiation - photoexcitation and and photoionization - on the ignition process?