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Appendix H

LOS ALAMOS NEP RESEARCH IN ADVANCED PLASMA THRUSTERS

Kurt Schoenberg and Richard Gerwin

Presented to the NASA
MPD Thruster Technology Workshop
May 16, 1991

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

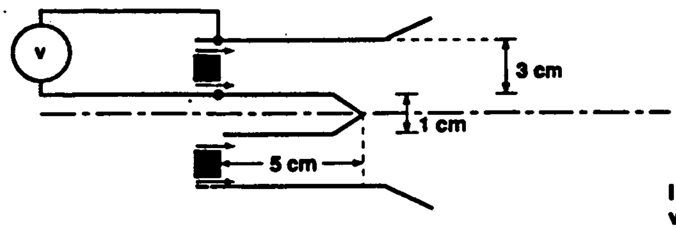
- **A CTX coaxial plasma gun, with tungsten-coated electrodes, is being operated as a function of current, gas pressure, gas type, applied axial magnetic field, and electrode polarity.**

- **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.

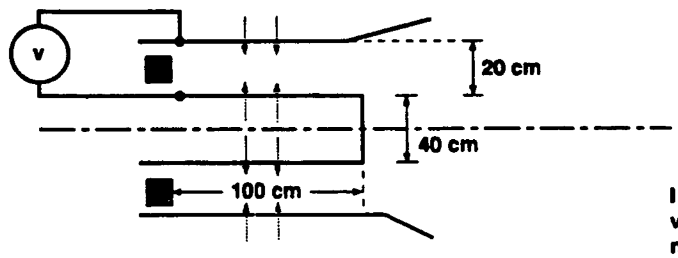
ELECTROMAGNETIC THRUSTERS: $J_r B_\phi$ DRIVES $\rho\dot{v}_z$

MPD THRUSTERS



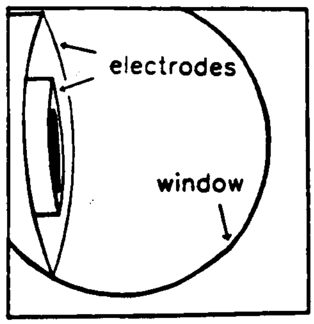
I ≈ few kA
v ~ 100 volts
n ≈ 10^{20} - 10^{21} m^{-3}

COAXIAL GUNS



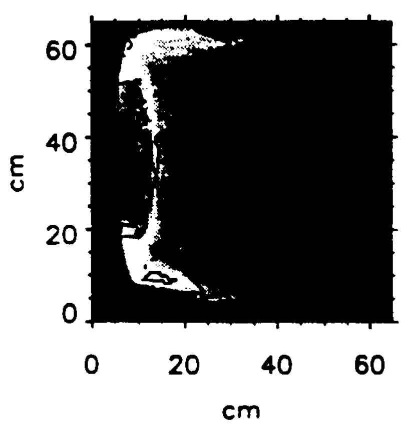
I ≈ 50-100 kA
v ≈ few 100 volts - few kV
n ≈ 10^{20} - 10^{21} m^{-3}

COAXIAL GUN DISCHARGE # CTX19645



Diagram

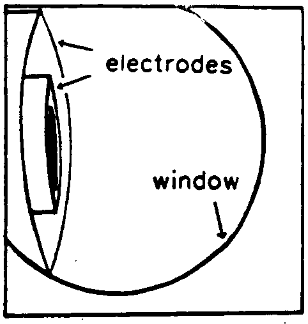
Visible Emission



Intensity Contours (0–255)

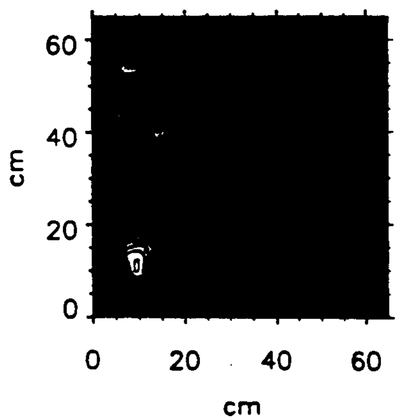
ORIGINAL PAGE IS
OF POOR QUALITY

COAXIAL GUN DISCHARGE # CTX19659



Diagram

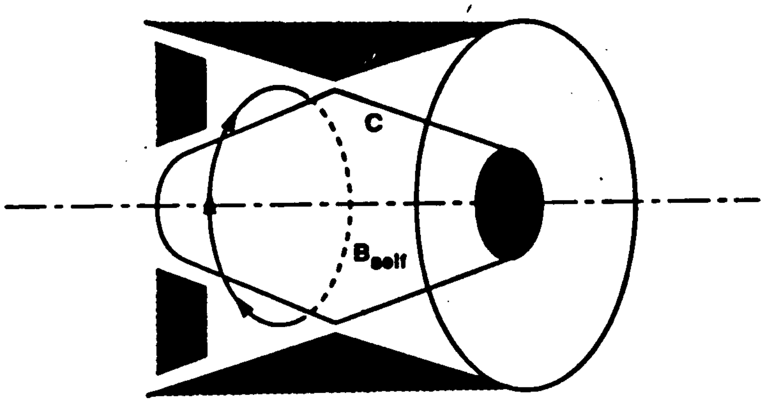
Visible Emission



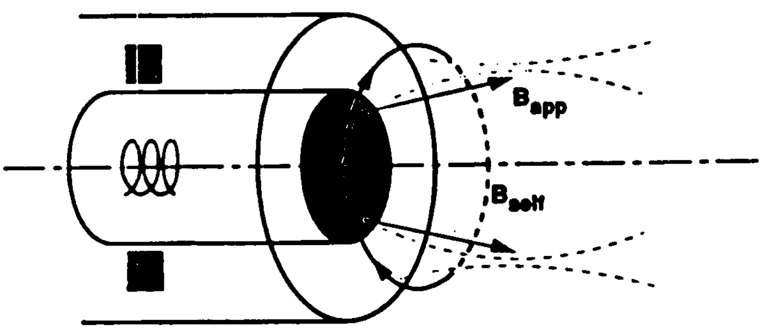
Intensity Contours (0–255)

DEFLAGRATION + NOZZLE = THRUST

BUILT-IN NOZZLE

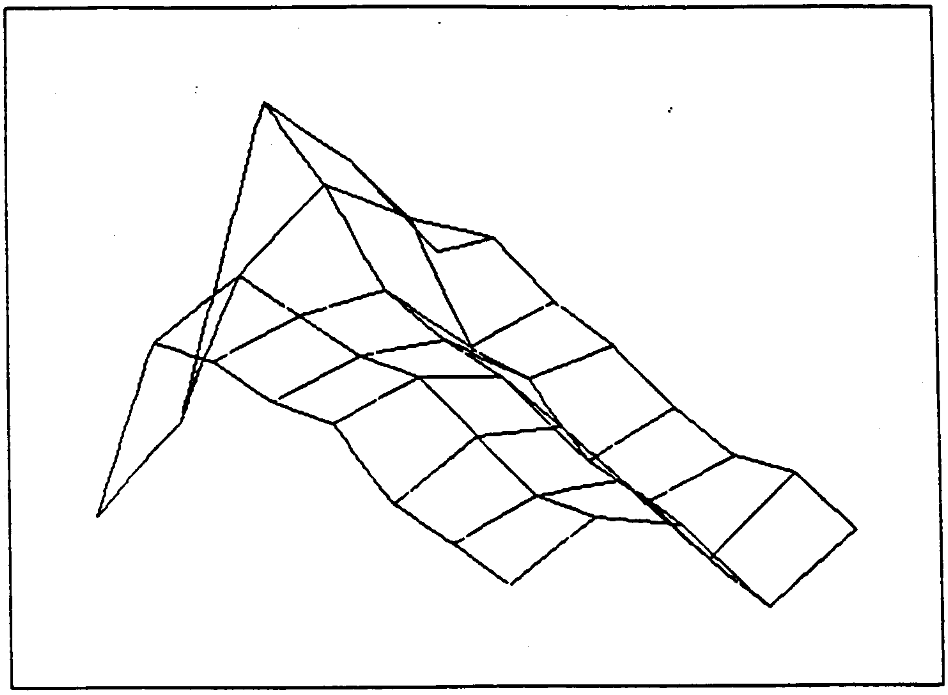


MAGNETICALLY-FORMED NOZZLE



PLASMA THRUSTER RESEARCH

Spatial Field Measurements



3-D Spatial | B | plot

ADVANCED PLASMA THRUSTERS

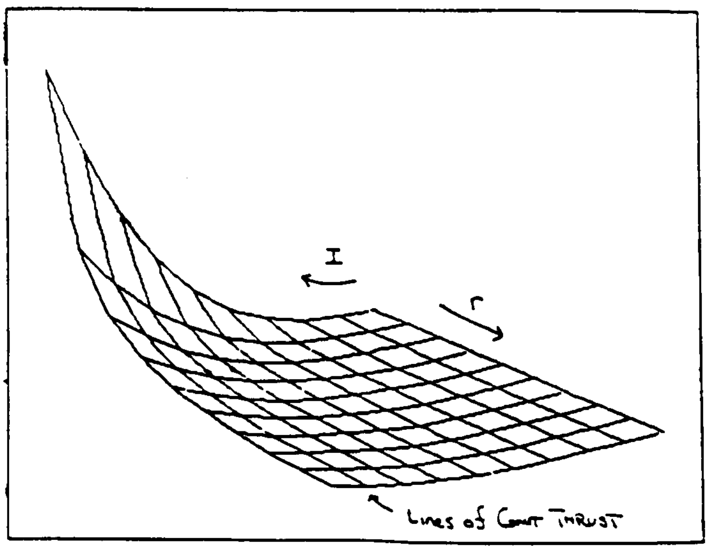
The Importance of Scale

- 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

ADVANCED PLASMA THRUSTERS

The Importance of Scale



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

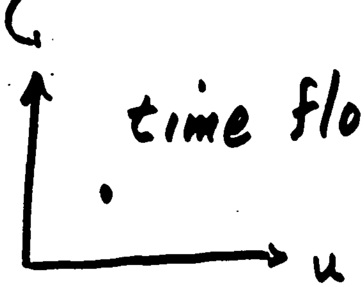
SCALING ISSUES FOR MPD THRUSTERS

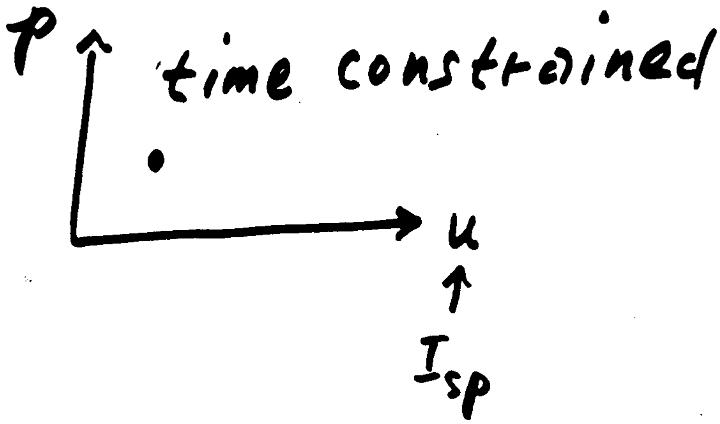
– Possible Reasons for Scaling with R –

- Mission Scaling
- Transport Scaling
- Macroscopic Stability
- Microscopic Stability
- Optimization of Thruster Efficienc

SCALING ISSUES FOR MPD THRUSTERS

– Mission Scaling –





In either case,

— M_{En}, M_{pr}, M_{GP} all scale with m_{pr}. —

where $m_{pr} \equiv \frac{1}{2} N_{th} \rho_0 A_0 f$ $\left(f \equiv V_0 / V_e \right)$.

Note: $m_{pr} \sim N_{th} \rho R^2$ (fixed $\frac{\Delta}{R}$)

— $I \sim R \rho^{1/2}$ for fixed I_{sp}. —

m_{pr}: "specific mass of the propellant"

— 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: $\left(\frac{d}{dt} = \frac{\partial}{\partial t} + \vec{V} \cdot \nabla \right)$

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

= Ohmic Heating + Viscous Heating

– Thermal Conduction Loss

$$\left.\begin{aligned} &+ n_0 \langle \sigma v \rangle_0^i \left[\tfrac{1}{2} m_i V^2 - \tfrac{2}{\gamma - 1} T - e_i \right] \\ &+ n_* \langle \sigma v \rangle_*^i \left[\tfrac{1}{2} m_i V^2 - \tfrac{2}{\gamma - 1} T - (e_i - e_*) \right. \\ &\qquad\qquad \left. - \frac{n_0 \langle \sigma v \rangle_0^* \, e_*}{n_* \langle \sigma v \rangle_*^i} \right] \end{aligned}\right\} \text{CIV!}$$

ionization of excited states:

where $\frac{1}{2} m_i V^2$ means $\frac{1}{2} m_i (V - V_m)^2$.

– Transport Scaling –

- Mass Transport $(\omega_{ce} < \nu_e)$

$$\frac{t_\eta}{t_z} \sim \mathcal{R}_{mag} \sim \left(\frac{V_z \Delta}{D_\eta}\right) \sim T^2 R$$

$$\sim \left(\frac{I}{R\rho^{1/2}}\right)^4 R$$

- Mass Transport $(\omega_{ce} > \nu_e)$

$$\frac{V_r t_z}{\Delta} \sim \frac{c/\omega_{pi}}{R}$$

[Ions carry some current.]

- Heat Transport by classical ions

$\dot{q}_i \left[\frac{MW}{m^2}\right]$ (next slides)

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

$\left(\frac{1}{2} m_i V^2 \gg \Delta e \text{ (atomic)}\right)$

$$T_i(eV) = 5.0 \times 10^{10} \left(\frac{I^2}{nr^2}\right)_{MKS}$$

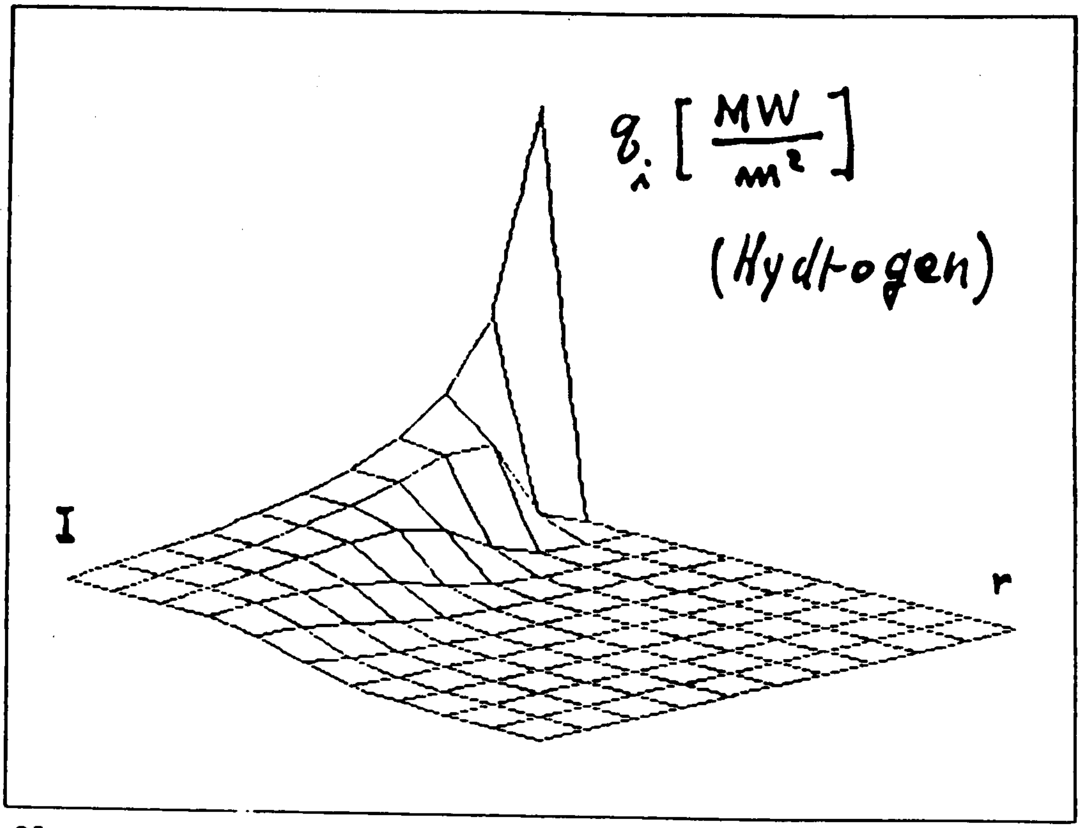
$$\frac{\omega_{ci}}{\nu_{ii}} = 4.6 \times 10^{29} \left(\frac{I^4}{n^{5/2} r^4}\right)_{MKS}$$

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

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

$$R_v = 0.58 \times 400 \times 10^{-40} \left(\frac{n^3 r^5}{I^4}\right)_{MKS} \left(\frac{\Delta}{r}\right) \left[1 + 3\left(\frac{\omega_{ci}}{\nu_{ii}}\right)^2\right]$$

$QI_{i,j} := Qi\left[I_i, n_2, r_j\right]$ $\quad I_0 = 5 \cdot 10^3$ $\quad I_{10} = 5.5 \cdot 10^4$ $\quad r_0 = 0.01$ $\quad r_{10} = 0.51$ $\quad n_2 = 3 \cdot 10^{20}$



QI

$QI_{0,0} = 15.448$ $\quad QI_{0,10} = 2.3 \cdot 10^{-10}$

$QI_{10,0} = 1.406$ $\quad QI_{10,10} = 0.004$

– 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 —

($\omega_{ci} > \nu_i$ case)

Viscous Reynolds number: $\dfrac{V\Delta}{D_v} = \mathcal{R}_v$

Ion Shear Viscosity: $\dfrac{1}{7}\,\dfrac{v_{thi}^2}{\nu_i}\,\dfrac{\nu_i^2}{\omega_{ci}^2} = D_v$

$\nu_i = \text{const.} \times n\, T^{-3/2}$

Hence $\mathcal{R}_v = \text{const.} \times \Delta \times \left(V\, \dfrac{B^2}{n}\, T_i^{1/2} \right)$

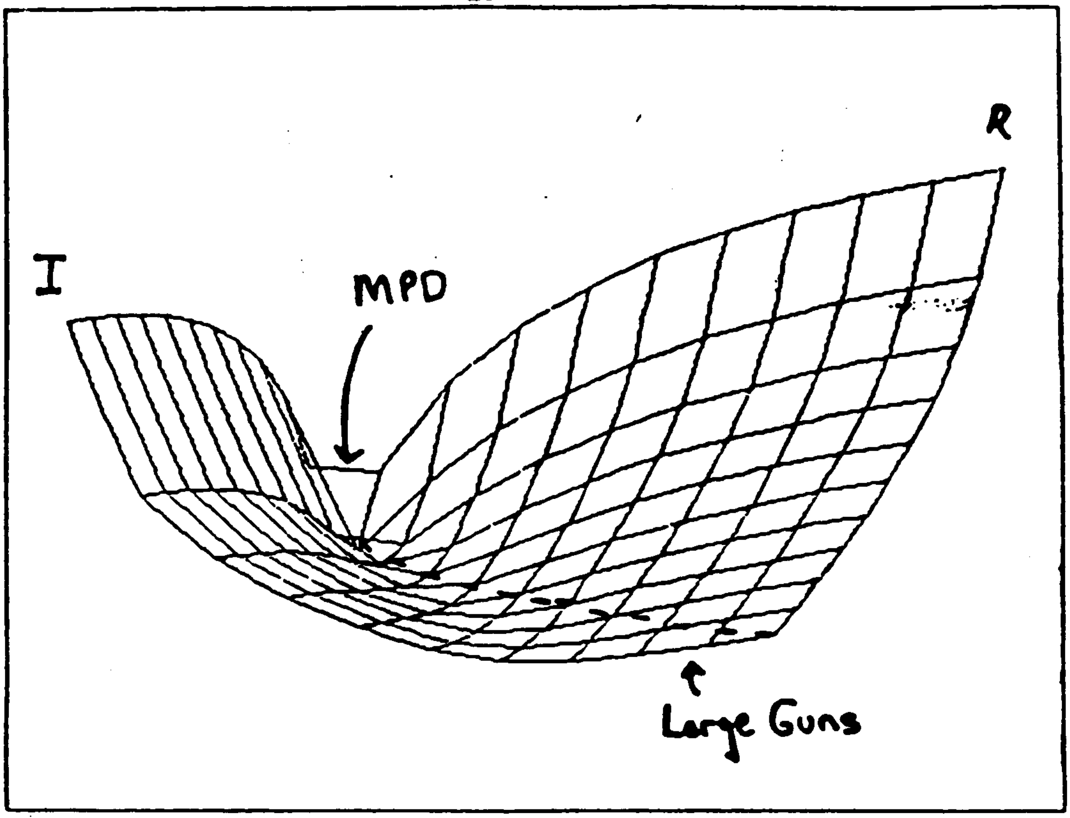
If T_i "does scale" (like V^2)

then $\mathcal{R}_v = \text{const.} \times \Delta \times V^4 \sim \left(\dfrac{I^2}{\dot{M}} \right)^4$

Scaling Issues for MPD Thrusters

$RV1_{i,j} := \log\left[Rv\left[I_i, n_1, r_j\right]\right]$ $I_0 = 5\cdot10^3$ $r_0 = 0.01$ $n_1 = 2\cdot10^{20}$

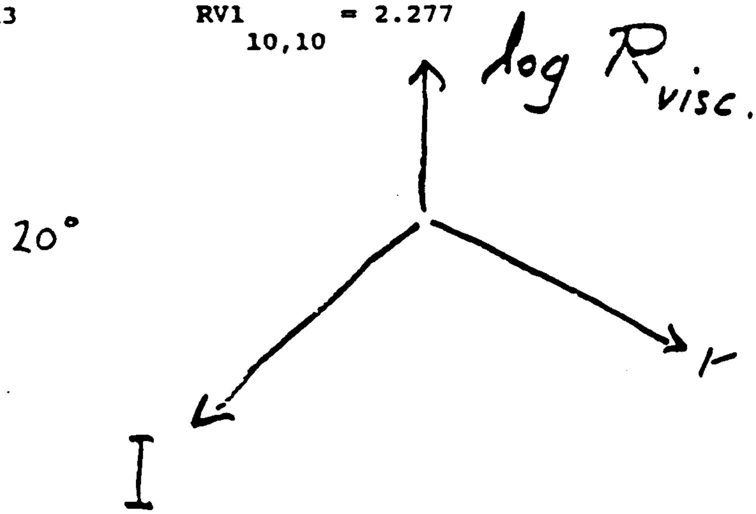
$I_{10} = 5.5\cdot10^4$ $r_{10} = 0.51$



RV1

$RV1_{0,0} = 2.964$ $RV1_{0,10} = 6.107$

$RV1_{10,0} = 7.13$ $RV1_{10,10} = 2.277$



— Microscopic Stability —

$V_{dr,R} \lesssim v_{thi}$ (threshold)

equivalent to

$$\frac{I^2}{\dot{M}} \lesssim \frac{4\pi}{\mu_0} \frac{R}{(c/\omega_{pi})} v_{thi}$$

If (T_i does not scale with V^2)

Then $\frac{I^2}{\dot{M}} \lesssim$ approx. const.

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

Then $\frac{I}{\dot{M}} \lesssim$ const. ← [observed at hi I]