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Appendix I

MPD WORK AT MIT

by

M. Martinez-Sanchez

D.E. Hastings

PRESENTED AT THE MPD THRUSTER TECHNOLOGY WORKSHOP

NASA HEADQUARTERS, MAY 16, 1991

GOALS VS. ACHIEVEMENTS

	EFFICIENCY (%)	I_{sp} (sec).	CATHODE EROSION (μg/C)
GOALS	50%	5000	10^{-4}
SELF FIELD MPD	42% (H_2 Ref. 1) 30% (A, Ref. 2)	6000 (H_2, Ref. 1) 3000 (A, Ref. 2)	2×10^{-3} (H_2, Ref. 9) 6×10^{-4} (N_2, Ref. 9) 1.3×10^{-3} (A, Ref. 9)
APPLIED FIELD MPD	70% (Li, Ref. 3) 70% (H_2, Ref. 4) 50% (NH_3, Ref. 4)	6800 (H_2, Ref. 5) 5800 (Li, Ref. 3) 2800 (A, Ref. 6)	3×10^{-5} (H_2, Ref. 7) 2×10^{-3} (NH_3, Ref. 8)

1. Uematsu, K et al, 1984
2. Wolff, M. et al, 1984
3. Connolly, D.J. et al 1968
4. Tahara, H, et al, 1988
5. Arakawa Y. et al., 1987
6. Connolly et al, 1971
7. Ducati, A.C. et al, 1964
8. Esker, D.W., 1969
9. Auweter-Kurtz, M., et al, 1990

ROADBLOCKS

PERFORMANCE FEATURE	LIMITING EFFECT	COMMENTS
THRUST EFFICIENCY	FROZEN LOSSES	- HIGHEST AT "ONSET" - LIMITING IONIZATION/KINETIC ENERGY, (MAY DEPEND GEOMETRY)
	ELECTRODE DROPS	- FORCE SELF-FIELD MPD TO MW POWER - LESS IMPORTANT WITH APPLIED FIELD
SPECIFIC IMPULSE	VARIOUS FORMS OF "ONSET"	- HIGHEST WITH LIGHTEST GASES
LIFE (EROSION)	ELECTRODE EVAPORATION	- THERMAL DESIGN, IMPREGNANT DISPENSER
	GAS IMPURITIES	- COMPOSITION CONTROL
	CATHODE MICROARCS	- MAY BE IRRELEVANT FOR HOT OPERATION
	MASSIVE ARCS AT ONSET	- ULTIMATE LIMITER

THE MIT PROGRAM

- SUPPORTED BY AFOSR GRANTS (1983 - PRESENT)
- MAINLY THEORETICAL WORK, WITH TWO EXCEPTIONS:
  - JOINT PROGRAM WITH R & D ASSOCIATES (HEIMERDINGER, KILFOYLE)
  - JOINT PROGRAM WITH PHILLIPS LAB (GAIDOS)
- HAS CONCENTRATED ON MODELING FLUID DYNAMICS AND PHYSICS OF SELF-FIELD THRUSTERS:

<u>1 - D MODELS</u>	DYNAMICS OF HIGH MAGNETIC REYNOLDS NO. FLOWS EFFECTS OF AREA CONTOURING EFFECTS OF KINETICS, TRANSPORT
<u>2 - D MODELS</u>	ANODE DEPLETION AND OTHER HALL EFFECT CONSEQUENCES FRICTION, DIFFUSION, HEAT LOSS DEVELOPMENT OF MACROSCOPIC INSTABILITIES
<u>STABILITY</u>	IONIZATION, LOWER HYBRID AND ELECTROTHERMAL INBSTABILITIES
<u>KINETICS</u>	UPPER LEVEL POPULATIONS, INLET EFFECTS

WHO DID (DOES) WHAT

	1-D Models	1 1/2-D Models	2-D Models (Numerical)	2-D Models (Analytical)	Stability Theory	Radiation, kinetics	Experimental
D. Heimerdinger (Ph.D)	Contouring	Anode Depletion					Contoured Channel
Tze Wing Roon (MS)					Ionization Stability		
D. Kilfoyle (MS)							Exit plane Spectroscopy
J.M. Chanty (Ph.D. cand.)	High R_m		Low Interaction	Asymptotics			
Eli Niewood (Ph.D. cand.)	Physics		Hall, t-accurate		Lower Hybrid		
Scott Miller (Ph.D. cand.)			Transport effects				
Jeff Preble (MS)					Electro-thermal		
Eric Sheppard (Ph.D. cand.)				Inlet Effects		Radiation, Kinetics	
Eric Gaides (Ph.D. cand.)							Onset Physics
M. Martinez-Sanchez	High R_m Contouring	Anode Depletion		Asymptotics	Electro-thermal		
D. Hastings					Lower Hybrid		

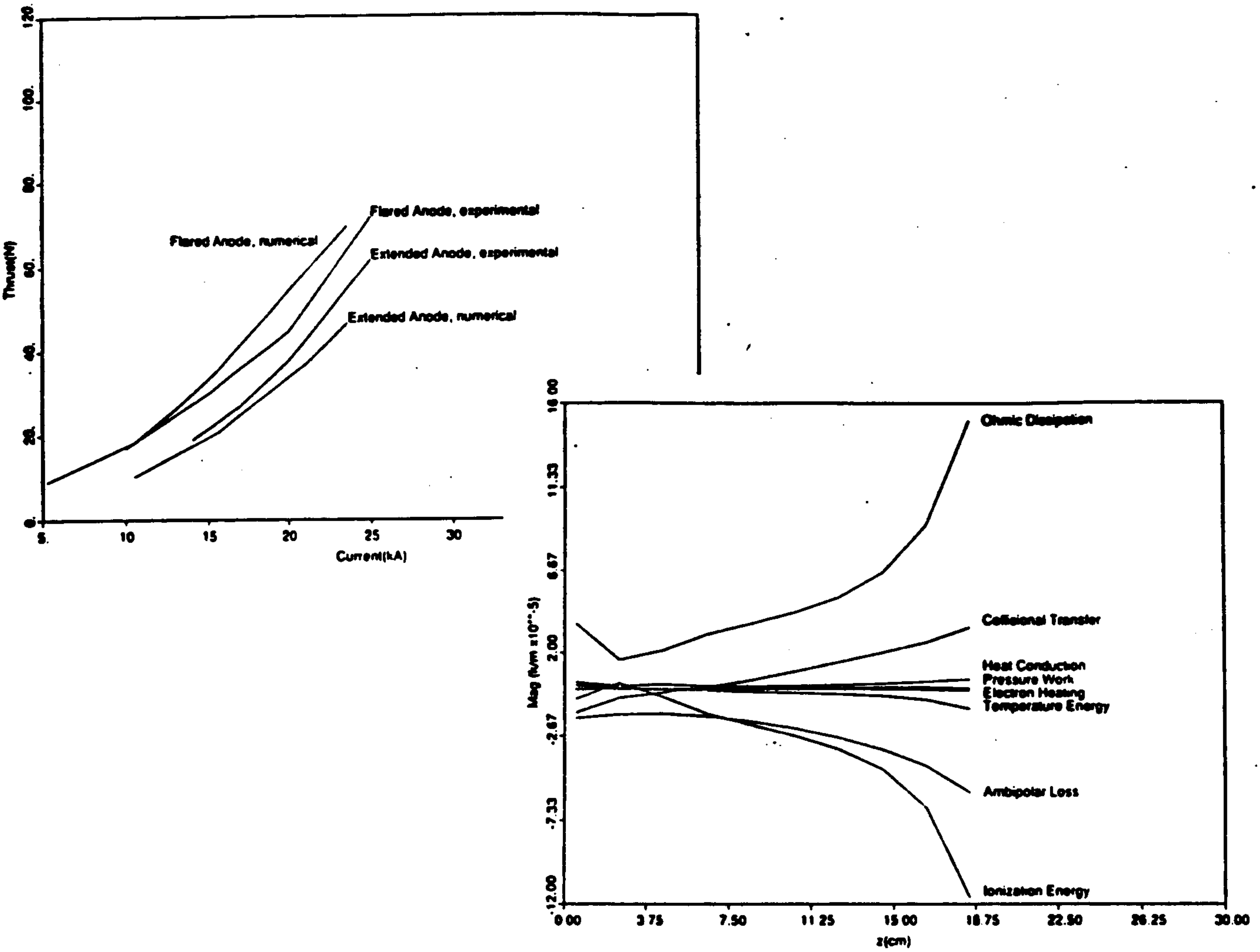
QUASI ONE DIMENSIONAL MODELING

- BY SACRIFICING GEOMETRICAL DETAIL, EXPLORATION OF A BROAD RANGE OF PHYSICAL EFFECTS IS POSSIBLE IN THE CONTEXT OF 1-D MODELS WITH AREA VARIATION

- SHOWN ARE EXAMPLES OF E. NIEWOOD'S RESULTS ILLUSTRATING

  (a) DEGREE OF AGREEMENT WITH THRUST DATA FROM TWO PRINCETON U. THRUSTERS

  (b) RELATIVE IMPORTANCE OF VARIOUS ELECTRON ENERGY SOURCES/SINKS ALONG THE LENGTH OF A THRUSTER

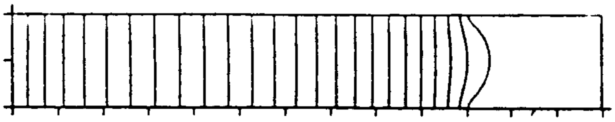


TWO-DIMENSIONAL MODELING - TRANSPORT EFFECTS

- VISCOUS DRAG IMPORTANT IN SLENDER THRUSTERS
- VISCOUS DISSIPATION CONTRIBUTES TO HIGH ION TEMPERATURE
- DIFFUSION AND HEAT CONDUCTION IMPORTANT AS DAMPING EFFECTS
  - RESULTS BELOW FROM S. MILLER'S WORK, FOR D. HEIMERDINGER'S CHANNEL, NEGLECTING HALL EFFECT.
  - NOTICE BOUNDARY LAYER DEVELOPMENT TO NEAR-FULLY DEVELOPED FLOW.
  - LACK OF SYMMETRY IS REAL, AND ARISES FROM ENERGY TRANSPORT BY TRANSVERSE CURRENT.

Two-Dimensional Viscous MPD Flow

Magnetic Field

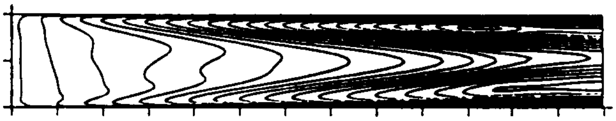


Max = 0.1T
Min = 0.0T
Inc = 0.004T

Fluid Velocity

Max = 5000m/s
Min = 0 m/s
Inc = 200m/s

Gas Temperature



Max=10000K
Min = 0K
Inc = 400K

TWO-DIMENSIONAL MODELING - HALL EFFECT

- THE HALL EFFECT STRONGLY DISTORTS THE PLASMA FLOWS, AS SHOWN IN THE 2-D RESULTS SHOWN NEXT. CONDITIONS ARE

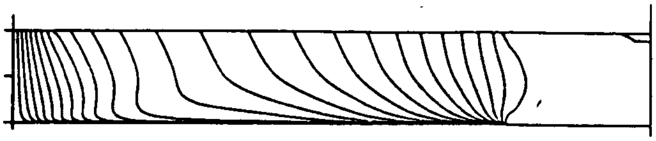
  $H = 2$ CM. $L = 10$ CM $B_O = 0.1$ T ($I \equiv 30$ kA)
  ARGON, $\dot{m} = 4$ g/sec

- NOTICE STRONG AXIAL CURRENT ALONG ANODE. THIS PRODUCES LARGE DISSIPATION (SEE T_e MAP) AND HIGH IONIZATION FRACTION. PLASMA IS KEPT ELECTROTHERMALLY STABLE BY ELECTRON HEAT CONDUCTION

- VERY STEEP VOLTAGE DROP NEAR ANODE FROM LOCALLY HIGH HALL FIELD. SEE POTENTIAL CUT IN NEXT GRAPH. THIS WAS SEEN IN OUR TESTS UNDER SIMILAR CONDITIONS (SEE BELOW)

Two Dimensional MPD with Hall Effect

Current Lines

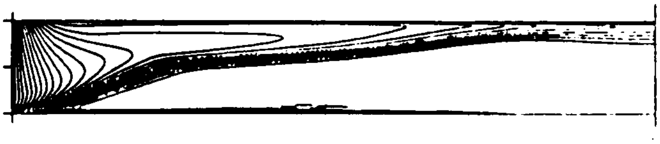


Max = 0.1 T
Min = 0.0 T
Inc = 0.002 T

Electron Temperature

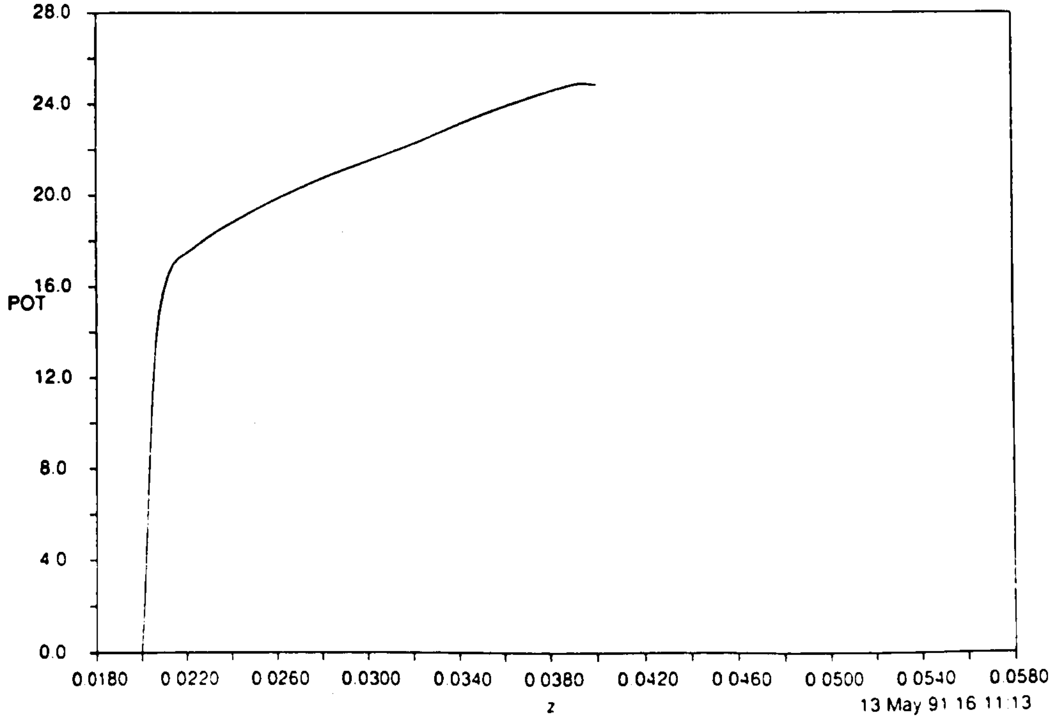
Max = 34000 K
Min = 10000 K
Inc = 500 K

Ionization Fraction



Max = 1.0
Min = 0.0
Inc = 0.02

2-D MPD EQUATIONS
POT



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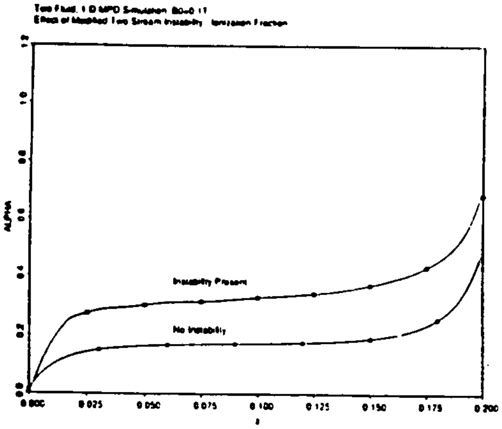
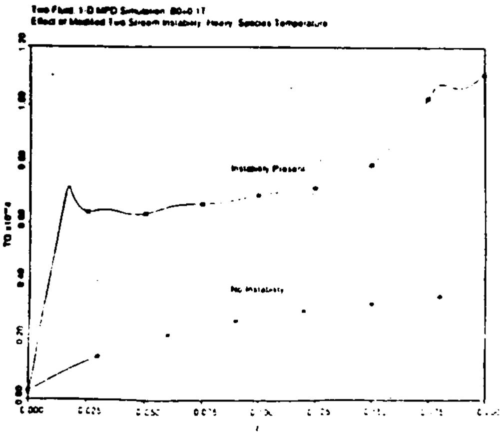
Microscopic Instabilities in MPD Flows

- Microscopic plasma instabilities have been shown to be common in many plasma regimes, eg. fusion plasmas, ionospheric plasmas.
- In MPD thrusters, current represents a large source of free energy, which may drive instabilities.
- Modified Two Stream instability was chosen as a likely candidate for importance in MPD.





Modified Two Stream Instability

Significant increases in heavy species temperature due to anomalous heating

Significant increase in ionization fraction due to increased dissipation

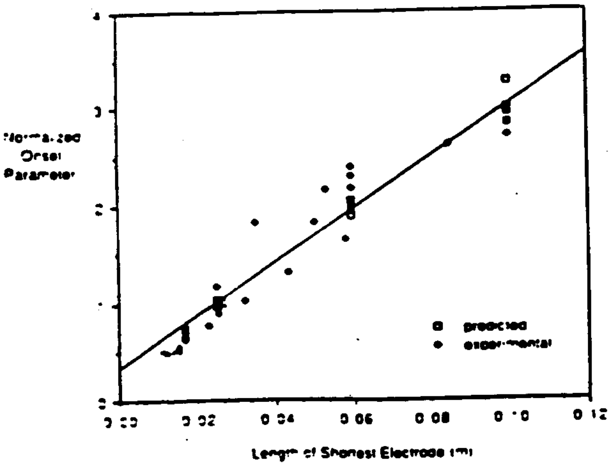
Increase in plasma resistivity but no macroscopic plasma instability

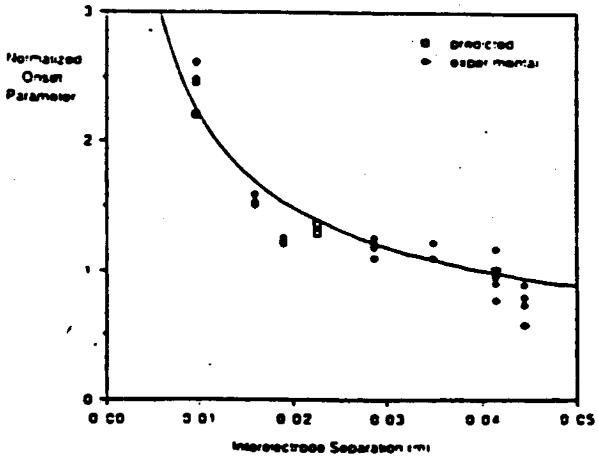
Conclusions

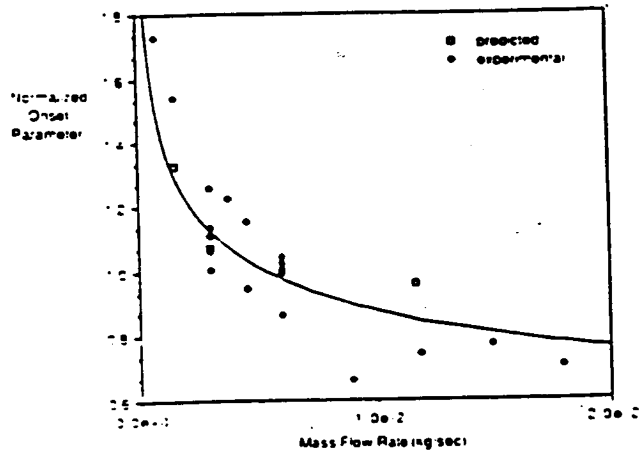
- Plasma can evolve to new equilibrium in presence of Modified Two Stream Instability, with increased ionization fraction and heavy species temperature.
- Microscopic plasma instabilities could lead to large variations in operating voltage and, therefore, efficiency.
- Plasma instabilities are important in modelling MPD flows.
- Experiments, both existing and, when required, new, should be used to ascertain what types of instabilities may be excited in MPD flows.

ELECTROTHERMAL STABILITY THEORY

- UNBOUNDED PLASMA BECOMES STATICALLY UNSTABLE NEAR FULL IONIZATION. CONDUCTIVITY $\sim T_e^{3/2}$, SO REGIONS OF HIGHER T_e TEND TO CHANNEL CURRENT, FURTHER RAISING T_e
- EFFECT IS MASKED AT PARTIAL IONIZATION BY ENERGY ABSORPTION IN IONIZATION PROCESS. SIMILARLY, HEAT DIFFUSION OR ELECTRON-ION PAIR DIFFUSION DAMPEN IT FOR SMALL (LESS THAN $\sim$ 2 - 4 CM) LENGTHS
- WE COUPLED A STANDARD STABILITY ANALYSIS WITH A 1-D MPD MODEL TO PREDICT CONDITIONS WHEN
  - (a) INSTABILITY WOULD DEVELOP SOMEWHERE (USUALLY AT EXIT)
  - (b) GROWTH RATE WOULD EXCEED SOME THRESHOLD
- RESULTS SHOW GOOD AGREEMENT WITH ONSET TRENDS VERSUS
  - (a) LENGH
  - (b) WIDTH
  - (c) MASS FLOW RATE (THIS DEVIATION FROM $I^2/\dot{m}$ SCALING WAS UNEXPLAINED BEFORE)







SEPARATION OF 'ONSET' AND ANODE DEPLETION

- FROM OUR COOPERATIVE WORK WITH R&D ASSOCIATES (HEIMERDINGER, 1988)
- USING QUASI - 2D CHANNEL AND 4g/sec. ARGON
- PROBE AT ~ 2 mm FROM ANODE DETECTS LARGE ΔV, AT ~ 30 KA (CLOSE TO THEORY PREDICTION), BUT PLASMA REMAINS "QUIET"
- AT 60 kA, LARGE, QUASI-PERIODIC VOLTAGE FLUCTUATIONS OCCUR
  - VERY CLEAR SEPARATION OF EFFECTS -

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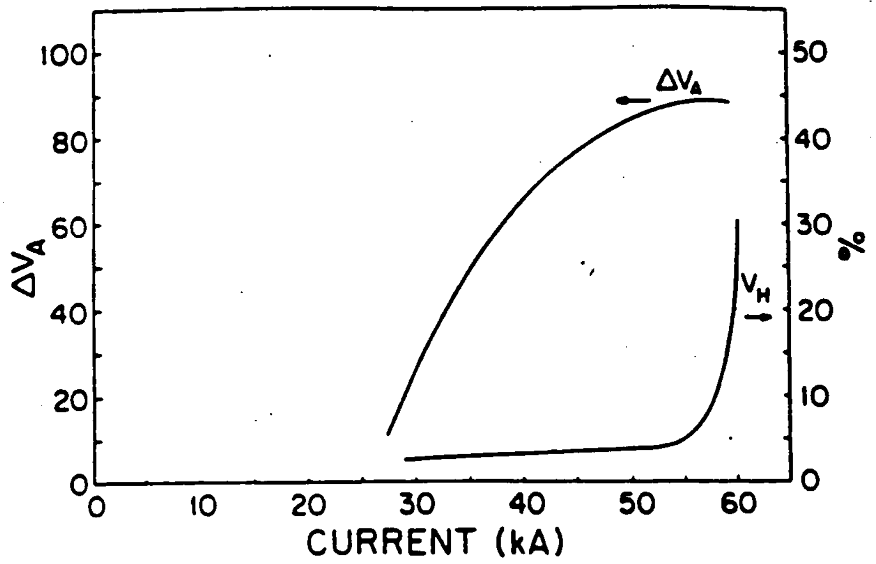
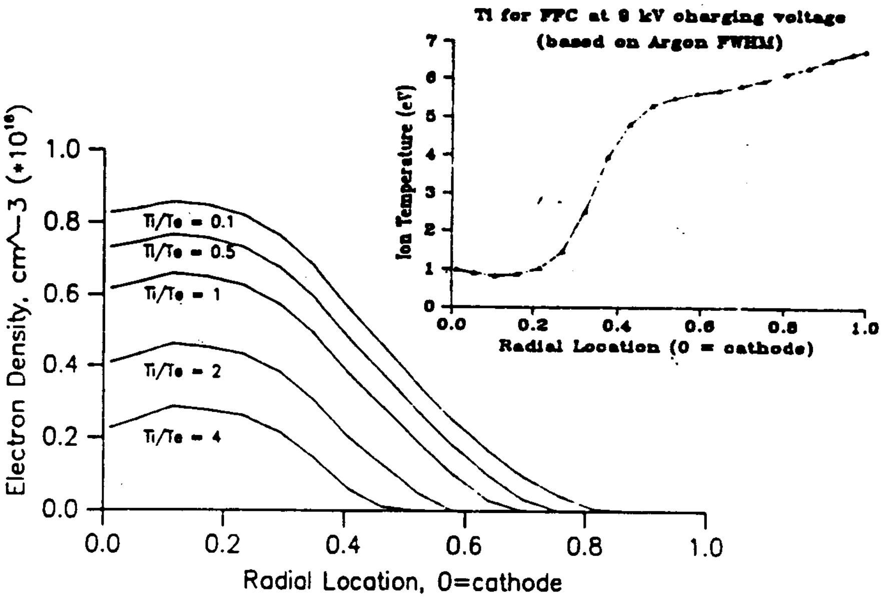


Variation of the Anode Voltage Drop and the Voltage Hash as a Function of the Thruster Current in the Fully Flared Channel for an Argon Mass Flow Rate of 4 g/s

EXIT PLANE SPECTROSCOPIC MEASUREMENTS

- DURING THE SAME TEST SERIES, D. KILFOYLE USED A 1.26 m. SPECTROSCOPE TO MEASURE LINE WIDTHS AND LINE INTENSITY RATIOS OF ARGON II AND H LINES (H_2 USED AS A DIAGNOSTIC ADDITIVE)
- DATA SHOW HIGH ARGON ION TEMPERATURES (HIGHER THAN T_e IN THE ANODE REGION), WHICH COULD IMPLY THE PRESENCE OF MICRO-INSTABILITIES
- DATA ALSO SHOW STRONG ANODE DEPLETION (AT $I = 60$ kA), IN AGREEMENT WITH ΔV_A DATA



Radial profile of electron density in fully flared channel for various assumed values of T_i/T_e

ONSET AS PERFORMANCE LIMITER. PHENOMENA

- AT HIGH CURRENT/LOW MASS FLOW SEVERAL PHENOMENA OCCUR (NOT ALWAYS SIMULTANEOUSLY WHICH LIMIT η, I_{sp} RANGE

	PHENOMENON	COMMENT
(a)	SHARP RISE IN UNSTEADINESS	MOST COMMON DEFINITION. PLASMA INSTABILITY LOCALIZED DOWNSTREAM
(b)	INCREASED WALL EROSION	CLOSELY ASSOCIATED TO (a) CURRENT CONCENTRATIONS
(c)	DEVELOPMENT OF LARGE ANODE DROP	NOT ALWAYS PRESENT. ALLEVIATED BY ANODE GAS INJECTION
(d)	TRANSITION $V \approx I$ TO $V \approx I^3$	PROBABLY UNRELATED, BUT HAS BEEN ASOCIATED WITH ONSET

- APPROXIMATE EMPIRICAL CORRELATION:

$$\frac{I^2}{\dot{m}} \sqrt{M} \equiv K \frac{L}{H}$$

I = CURRENT
$\dot{m}$ = FLOW RATE
M = MOLECULAR MASS
L = ACCELETATOR LENGTH
H = INTER-ELECTRODE DISTANCE
K = CONSTANT

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EXPLANATIONS OF ONSET (NO COMPLETE THEORY)

DESIGNATION	BASIC ASSUMPTIONS	PREDICTIONS	COMMENTS
(a) EQUIPARTITION, OR CRITICAL IONIZ. VELOCITY	'ONSET' OCCURS WHEN $eV_i = \frac{1}{2} m_i c^2$	$\eta_{FROZEN} = 1/2$ $\frac{I^2}{\dot m} = \frac{2}{\mu_0}\sqrt{\frac{2eV_i}{m_i}}\frac{W}{H}$ (W = CHANNEL DEPTH) (H = INTERELECTRODE DISTANCE)	· PROVIDES ROUGH CORRELATION OF MOST DATA
(b) ANODE DEPLETION	HALL AXIAL CURRENT FORCES PLASMA AWAY FROM ANODE. 'ONSET' WHEN $(n_e)_{ANODE} = 0$	$\frac{I^7 m_i^3}{\dot m^4} = \frac{945}{16}\frac{e\,k\,(T_e + T_g)}{\sigma\,\mu_0^4}\frac{L W^3}{H^5}$	· APPROXIMATELY SAME DEPENDENCIES AS DATA PRESUMPTION IS THAT ANODE SHEATH WILL BREAK DOWN
(C) FULL IONIZATION	ONE OF SEVERAL ANOMALOUS EVENTS OCCURS AS IONIZATION ENERGY SINK DISAPPEARS	$\eta_{FROZEN} = F(GEOMETRY)$ $\frac{I^2}{\dot m} = \frac{2}{\mu_0}\sqrt{\frac{2eV_i}{\mu_i}}\frac{W_0^2}{A^*}\frac{1}{\bar{u}_e}\sqrt{\frac{\eta_{FR}}{1-\eta_{FR}}}$ W_0 = DEPTH AT INLET $A^* = W^* H^*$ = THROAT AREA $\bar{u}_e = \frac{u_e}{u_{ref}}$ u_{ref} = VELOCITY FOR MOMENTUM = MAGNETIC FORCE	· A VARIATION ON (a) · PROVIDES MORE DETAIL. · STILL NO MECHANISN
(d) INSTABILITIES	SEVERAL PROPOSED: · IONIZATION INSTAB. · MICROINSTABILITIES OF TWO-STREAM TYPE · STATIC ELECTROTHERMAL	INSTABILITY THRESHOLD (DEPENDS ON TYPE) · DOMINANT WAVELENGTH · FREQUENCIES · HEATING EFFECTS, ETC.	· ELECTROTHERMAL INSTAB. PROVIDES MECHANISM FOR (C) · MICRO-INSTABILITIES MAY EXPLAIN HIGH T_i · ALL VERIFIABLE BY DETAILED PROBING

GEOMETRY EFFECTS ON ONSET

- BASED ON 1-D, VARIABLE AREA MODEL WITH P NEGLECTED. "ONSET" ASSUMED WHEN

$$V I - \frac{1}{2} \dot{m} u_E^2 = \dot{m} e V_i / m_i$$

- TWO CONTOURS: (a) CONSTANT AREA
  (b) CONV. - DIV. (SPACING CHOSEN FOR CONSTANT CURRENT DENSITY

- LENGTH MEASURED BY MAGNETIC REYNOLDS NO. BASED ON ALFVEN CRITICAL SPEED:

$$R_{m_A} = \mu_o \sigma V_A^* L \qquad \left(V_A^* = \sqrt{\frac{2 e V_i}{m_i}} \right)$$

- TWO MEASURES OF "ONSET"

(1) NORMALIZED $I^2/\dot{m}$ $: Y = \frac{U_{ref}}{V_A^*}, \qquad U_{ref} = \left(\frac{1}{2} \mu_o \frac{A^*}{W_o^2} \right) \frac{I^2}{\dot{m}}$

(2) NORMALIZED EXIT VELOCITY: $Z = \frac{U_E}{V_A^*}$

- RESULTS SHOW SIGNIFICANT GAINS IN η_{FR} AND I_{sp} BY CONTOURING
- BUT NO GAINS OF $I^2/\dot{m}$ - SHOWING LIMITATIONS OF $\frac{I^2}{\dot{m}}$ PARAMETER
- GAINS HIGHEST AT LARGE R_{m_A}

ONSET AT FULL IONIZATION - CONSEQUENCES

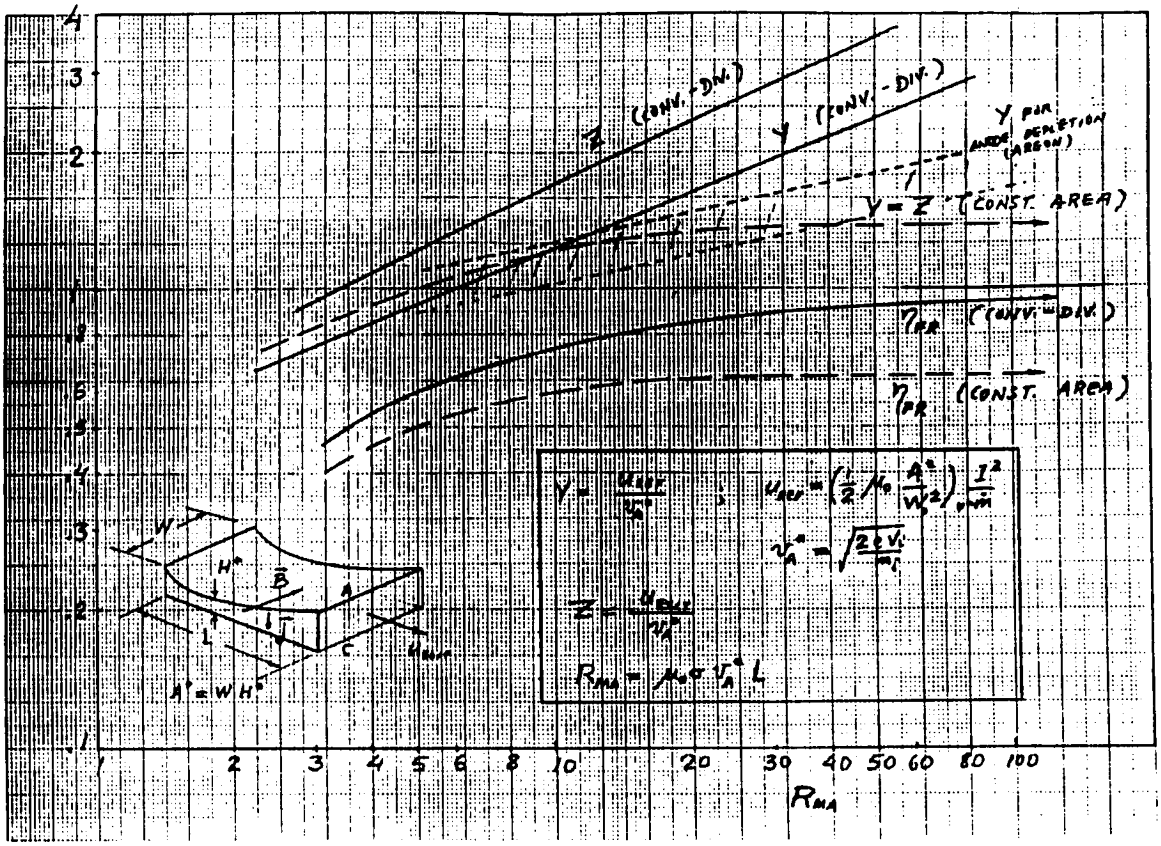
- PREBLE'S WORK ON ELECTROTHERMAL INSTABILITY PREDICTS CORRECTLY SEVERAL TRENDS, <u>INCLUDING DEVIATIONS FROM</u> $I^2/\dot{m}$ <u>RULE</u>.

- ELECTROTHERMAL INSTABILITY SEEN TO OCCUR AT $\alpha \cong 0.9$ ONLY. HOWEVER, 'FULL IONIZATION' IS NECESSARY FOR INSTABILITY, NOT SUFFICIENT.

  (a) GROWTH MAY BE WEAK IN PASSAGE TIME
  (b) IN SMALL CHANNELS OR AT LOW PRESSURES, DIFFUSIVE EFFECTS PROVIDE STABILITY

- THEORY STILL TOO CRUDE (LINEAR, CONSTANT BACKGROUND, NO ION DYNAMICS...)

  HOWEVER, GIVEN ITS SUCCESS, IT IS INTERESTING TO EXPLORE CONSEQUENCES OF 'FULL IONIZATION' MODEL



RELATIONSHIP TO ANODE DEPLETION

- ANODE DEPLETION LIMIT INCREASES ONLY WEAKLY WITH LENGTH (R_{MA}). HENCE, IF R_{MA} IS INCREASED IN ORDER TO GAIN EFFICIENCY AND I_{sp}, DEPLETION MAY HAPPEN BEFORE ONSET.

- THIS WAS CLEARLY OBSERVED IN OUR OWN TESTS. ALSO SEEN BY KURIKI ET AL. (AIAA-81-0683) IN KIII THRUSTER. HERE, ΔV_A FIRST INCREASED GREATLY WITH CURRENT, THEN COLLAPSED AS ONSET FLUCTUATIONS OCCURRED.

- THE GRAPH ALSO SHOWS A BAND OF PREDICTED DEPLETION NORMALIZED $I^2/\dot{m}$ PARAMETER (Y) FOR ARGON. FOR H_2, THRUSTERS MAY ENCOUNTER DEPLETION FIRST.

- NOTICE THAT (PARTICULARLY FOR CONSANT AREA), DEPLETION AND FULL IONIZATION HAPPEN (IN ARGON) AT ABOUT THE SAME TIME FOR THE IMPORTANT R_{MA} RANGE. THIS HAS BEEN NOTED REPEATEDLY, AND HAS BEEN A SOURCE OF CONFUSION.

SUMMARY ON SELF-FIELD MPD

- EFFICIENT ONLY AT HIGH POWER DUE TO LOW VOLTAGE, LARGE ELECTRODE LOSSES.
- HIGH POWER OPERATION LIMITED BY "ONSET"
- PHYSICS OF ONSET NOT YET CLEAR, BUT IT APPEARS TO DICTATE RATIO OF FROZEN LOSS TO KINETIC ENERGY. HOWEVER, THIS RATIO MAY BE CONTROLLED BY DESIGN.
- ANODE DEPLETION IS SEPARATE LIMITER, ESPECIALLY FOR LONG CHANNELS. SHOULD DESIGN FOR COINCIDENT ONSET AND DEPLETION (OR FIND WAYS TO REDUCE ΔV_{ANODE}) .
- LIFE ISSUES DIFFICULT, BUT PROGRESS IS ENCOURAGING
- SPECIFIC IMPULSE APPEARS SUFFICIENT IF USING H_2 OR Li

APPLIED FIELD MPD - THE LOGICAL GROWTH PATH

- NO TECHNOLOGY FOR HIGH I_{sp}, COMPACT THRUSTERS IN THE 50 - 100 KW RANGE
- AF - MPD POORLY UNDERSTOOD, BUT HAS SHOWN POTENTIAL TO FILL THIS ROLE. IN ADDITION, NO APPARENT HIGH POWER LIMIT (MAY BECOME SF AT HIGH POWER)

THE CASE FOR AF

A-PRIORI ARGUMENTS:

(a) INCREASED IMPEDANCE DUE TO $U_\theta B_x$ VOLTAGE LESSEN IMPACT OF ELECTRODE ΔV's - SHOULD ALLOW FOR POWER OPERATION.

(b) PLASMA ROTATION REDUCES ELECTRODE DAMAGE BY ARCS OR OTHER FAULTS - MAY ALLOW POST-ONSET OPERATION.

(c) MAGNETIC CONFINEMENT SHOULD HELP PROTECT WALLS - REDUCE WALL LOSSES, LENGTHEN LIFE.

(d) MAGNETIC NOZZLE SHOULD ALLOW SOME FROZEN LOSS RECOVERY BY EXTERNAL EXPANSION.

THE CHALLENGES OF AF MPD

(a) ADDED OPERATIONAL COMPLEXITY. BUT SEE RECENT WORK (TAHARA ET AL., ARAKAWA ET AL.) SHOWING POTENTIAL FOR SERIES LOOPS OR PERMANENT MAGNETS.

(b) INCREASED TESTING DIFFICULTIES (LONG MAGNETIZED PLUME). BUT LOW POWER OPERATION TO COUNTER.

(c) GREAT PHYSICAL COMPLEXITY. THRUST - PRODUCING MECHANISMS STILL DEBATED. SPATIAL-TEMPORAL UNIFORMITY NOT GUARANTEED. REGIMES OF OPERATION UNCHARTED.

RECOMMENDATIONS

- REPRODUCE AND VERIFY SELECTED APPLIED FIELD MPD EXPERIMENTS FROM EARLY LITERATURE AND/OR FROM ABORAD.
- SUPPORT THEORY/MODELING WORK ON AF THRUSTERS TO EXPLOIT EXISTING COMPUTATIONAL CAPABILITIES.
- CONTINUE QUASI-STEADY SF AND AF TESTING TO STUDY DETAILED PLASMA MECHANISMS RESPONSIBLE FOR "ONSET" AND OTHER BULK EFFECTS.
- USE 100 - 500 KW STEADY STATE FACILITIES FOR

(a) STUDIES OF ELECTRODE LIFE AND THERMAL DESIGN FOR BOTH, AF AND SF THRUSTERS.

(b) PERFORMANCE MAPPING AND SYSTEM INTEGRATION FOR AF THRUSTERS.