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THEORY OF PLASMA CONTACTORS FOR ELECTRODYNAMIC TETHERED SATELLITE SYSTEMS

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THEORY OF PLASMA CONTACTORS FOR ELECTRODYNAMIC TETHERED SATELLITE SYSTEMS*

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ABSTRACT

Recent data from ground and space experiments indicate that plasma releases from an object dramatically reduce the sheath impedance between the object and the ambient plasma surrounding it. Available data is in qualitative accord with the theory developed below to quantify the flow of current in the sheath. Electron transport in the theory is based on a fluid model of a collisionless plasma with an effective collision frequency comparable to frequencies of plasma oscillations. The theory leads to low effective impedances varying inversely with the square root of the injected plasma density. To support such a low impedance mode of operation using an argon plasma source for example, requires $Ip - I_e/30$; that is, only one argon ion must be injected for each thirty electrons extracted from the ambient plasma. The required plasma flow rates are quite low; to extract one ampere of electron current requires a mass flow rate of about one gram of argon per day.

INTRODUCTION

The electrodynamic tethered satellite system requires the ejection of electrons from the shuttle at one end of the system and the collection of a compensating current by the satellite at the other end. While the simplest concept is to collect electrons on the subsatellite and to collect a corresponding number of positive ions on the shuttle orbiter, ion collection by the orbiter is acknowledged to be inadequate

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to support the desired levels of current. The baseline configuration has an electron gun mounted on the shuttle. To obtain ampere sized currents, assuming a perveance of 6×10^{-6} amperes/volt$^{3/2}$, requires thousands of volts across the gun. This voltage drop corresponds to an effective emission impedance of thousands of ohms. An alternative method of emitting electrons from the shuttle is creating a high density plasma in the vicinity of the shuttle. Calculations presented below show sheath impedances are dramatically reduced by the use of hollow cathode plasma sources.

Passive collection of ampere level electron currents by the tethered satellite is simple in concept; however, there is also a substantial sheath impedance associated with the flow of charge between the tethered satellite and the ambient space plasma environment. Theory[1] predicts that the extraction of amperes of electron current by a sphere of 1.5 meter diameter requires a potential of kilovolts. This high impedance collection is in substantial accord with the results of the Plasma Interaction Flight Experiment (PIX)[2] which collected only a few milliamperes of current with a kilovolt bias on a 2000 cm^2 solar panel. Both theory and flight data demonstrate clearly the need to increase the current flow between the TSS and the space plasma.

One way to collect more electrons is to increase the diameter of the tethered satellite, but this is impractical for TSS-1. Another way is to increase the plasma current in the vicinity of the subsatellite. This can be done by mounting a plasma source, such as a hollow cathode, on the subsatellite. The SEPAC electron beam experiments conducted on Space Lab I indicate plasma sources to be an effective means for neutralizing beam currents and controlling spacecraft potentials.[3] When a plasma cloud was ejected along with a 5 keV, 0.3 amp electron beam, the spectrum of returning electrons was confined to energies below the beam energy, and the orbiter potential was clamped to a small value on the order of 1 volt. When the plasma jet was not active, however, the electron energy spectrum developed a peak at 1.1 keV and there were significant fluxes of electrons above the primary beam energy. The SEPAC experiments provide clear evidence of the low impedance neutralization of a high current electron beam by a plasma plume.

The next section gives a brief review of some properties of hollow cathode sources. The following sections develop a model for estimating the impedance to current flow across the plasma produced by the hollow cathode source, and determines the rate of plasma production required to support a low impedance mode of current collection.

HOLLOW CATHODE PLASMA SOURCES

One device for generating a contactor plasma is the hollow cathode. Hollow cathode devices have played a prominent role in space applications, especially in the development of ion thrusters for solar electric propulsion systems. Ion beams ejected by ion accelerators were charge and current neutralized by electron currents flowing from the cathode through the plasma generated by the hollow cathode. The concept of the hollow cathode as a beam neutralizer was successfully incorporated into the SERT II satellite, and performed in space flight tests in the manner expected on the basis of tests conducted in high vacuum laboratory facilities.[4]

The hollow cathode is a compact, low impedance device. The simplified features of one such device are indicated schematically in Figure 1.[5]

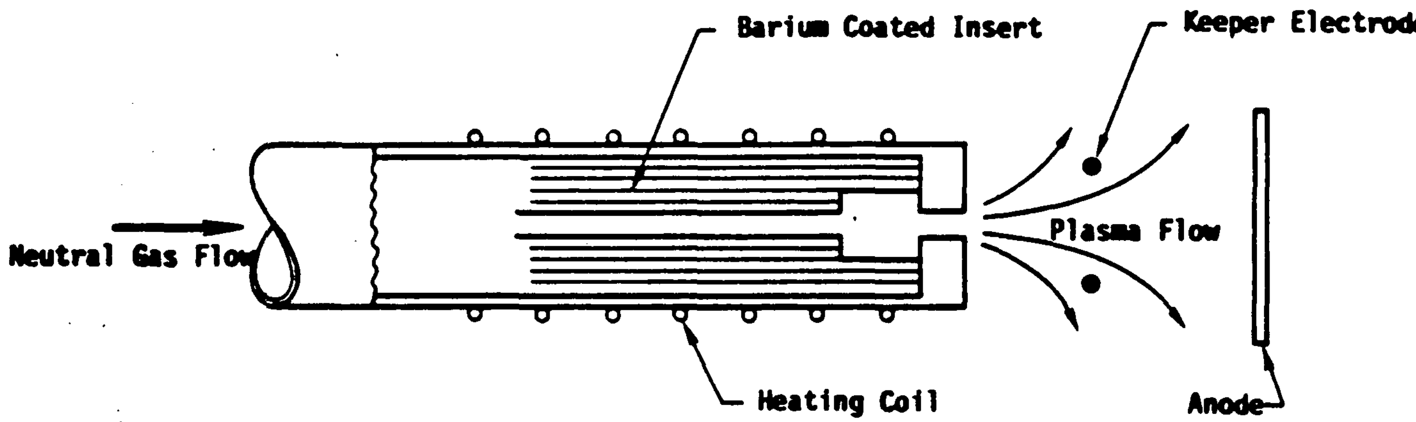

Figure 1. Schematic diagram of a hollow cathode configuration.[5]

A neutral gas, such as mercury or argon, flows into the cathode chamber where it is ionized by field accelerated electrons emitted from the coated insert or chamber walls through thermionic or other processes. The keeper electrode assists in initiating and in stabilizing the electrical discharge. With these devices nearly complete ionization of the neutral gas can be achieved, the resulting plasma flowing through the orifice at the net upstream flow rate. Various devices of this type have been operated at mass flow rates ranging from micrograms per second to grams per second, with currents ranging from milliamperes to kiloamperes.[5,6,7] For applications to the electrodynamic tethered satellite system, primary interest attaches to the low flow rate, low current range.

The hollow cathode used in the SERT experiment had a length of about 10 cm, an external diameter of about one-half centimeter and an orifice diameter of about 1 mm. It used Hg as the operating gas. Mercury flow rates of the order of 100 ma equivalent, or less, neutralized beam currents of order of 250 ma, while developing potential differences no greater than a few tens of volts between various vehicle surfaces and the neutralizing plasma. Hollow cathodes employed in the electrodynamic tether experiment may have physical characteristics similar to those used in the SERT test, but should be flexible enough to permit the generation of a substantial range of plasma densities near the vehicle.

Experiments show that the properties of the plasma generated by the hollow cathode depend upon whether it operates in its spot or plume mode.[5] More complete ionization, higher plasma densities and electron temperatures, and a lower electrical impedance of the discharge generally characterize the spot mode. The plume mode is characterized by less efficient ionization, a lower plasma density and a higher electrical impedance to the flow of discharge current than the spot mode. A higher rate of gas flow, shorter cathode to anode distance and a higher discharge current tend to produce the spot mode. Figure 2 shows an example of a measured discharge voltage current characteristic.[7]

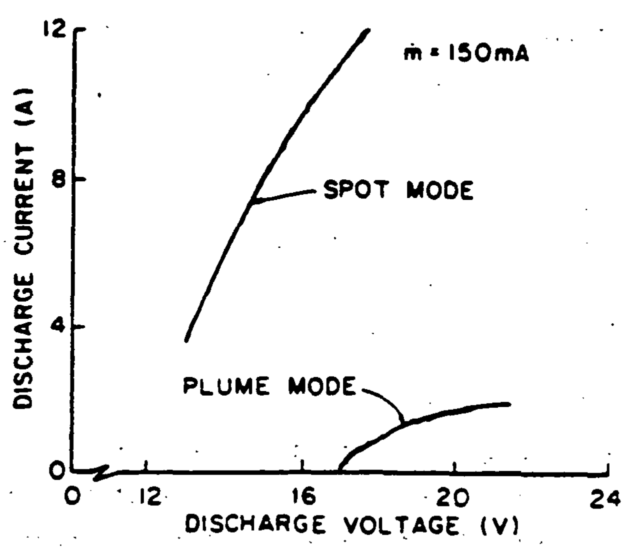

Figure 2. Discharge voltage-current characteristic.

HOLLOW CATHODES AS ELECTRON EMITTERS

Hollow cathodes have been used as plasma sources in ground test facilities and in space flight tests to charge and current neutralize ion beams of solar powered ion propulsion systems. In the space flight tests electrons were transported long distances from their source along the path of neutralized high energy ion beams. There have not been experiments which bear upon the question of how effectively electron currents may flow from hollow cathode sources into the ambient plasma in the absence of an ion beam. Thus, the conclusions reached below must be regarded as tentative.

Experiments conducted in ground facilities indicate that the plasma, despite long classical collisional mean free paths, appears to behave in a resistive manner.[8,9,10] Previous calculations of neutralizer plasmas showed that, at least for regions of several centimeters from the cathode orifice, the plasma properties and electron current flow patterns conformed to a fluid model of electron transport.

The basic elements of the model are the steady state ion continuity and momentum equations

$$\nabla \cdot n\vec{V} = 0 \tag{1}$$

$$M \frac{d\vec{V}}{dt} = e\left(E + \frac{\vec{V}\times\vec{B}}{c}\right) - \frac{\nabla p_i}{n} \tag{2}$$

where $n = n(\vec{r})$ is density of ions of mass M at the position $\vec{r}$ and $\vec{V}$ their mean velocity. The motion of the ion is influenced by the ambient magnetic field $\vec{B}$, the ion pressure p_i (both set to zero in previous studies), and the electric field in the quasineutral plasma. Quasineutrality, together with the assumption that electrons issuing from the cathode orifice satisfy the momentum balance equation

$$\nabla p_e + en\vec{E} = n\eta e\vec{j} \qquad (3)$$

relating the electron pressure,

$$p_e = n\theta \qquad (4)$$

the electric field, and the net current density $\vec{j}$. Here θ is the electron temperature in energy units and η is the resistivity. If the plasma is non-resistive, $\eta = 0$, and isothermal, Eq. (3) yields the Boltzmann law

$$n \propto \exp(e\phi/\theta) \qquad (5)$$

relating the density and the electric potential. In general the plasma resistivity η is related to an effective collision frequency ν by

$$\eta^{-1} = \frac{ne^2}{m}\,\nu^{-1} \qquad (6)$$

where m is the electron mass and where for a sufficiently dense and cold plasma ν is the classical electron ion collision frequency. If the plasma is not collision dominated, randomization of electron velocities may still occur through enhanced levels of fluctuating electric fields, such as occur in the unstable passage of electron streams through the plasma. These mechanisms are effective in coupling hollow cathode electrons into the plasma at effective collision frequencies that may be almost as large as the plasma frequency.[8] When augmented by an energy balance equation, two-dimensional calculations predict temperatures and potentials in reasonable agreement with ion engine neutralization data obtained both in the laboratory and in space.

This theory for electron transport can be applied in simplified form to electron emission to the space plasma. Consider a spherical source with its center chosen as the origin of a coordinate system. The plasma is assumed isothermal, and its density through space given by

$$n = \frac{n_o r_o^2}{r^2} \tag{7}$$

to a distance R where $n = n_{amb}$;

$$R = r_o \left(\frac{n_o}{n_{amb}}\right)^{1/2} \tag{8}$$

From Eq. (3)

$$\theta \nabla n - ne \nabla\phi = \eta nej = \eta ne \frac{I}{4\pi r^2} \tag{9}$$

where I is the total current transported to the ambient plasma ($I < 0$ for net electron flow outward).

Integrating

$$-\frac{\theta}{e} \ln \frac{n_o}{n_{amb}} + \phi(r_o) = \frac{I}{4\pi} \int_{r_o}^{R} \eta(r) \frac{dr}{r^2} \tag{10}$$

For a collisionless plasma, η is greatest for strong turbulence, and the effective collision frequency ν is[11]

$$\nu = \alpha \omega_p \tag{11}$$

where α is a number of order unity and $\omega_p = \sqrt{4\pi n_e^2/m}$ is the plasma frequency.

Utilizing Eq. (6) and the density given by Eq. (7), we obtain

$$\phi_o(r_o) = \theta \, \ln \frac{n_o}{n_{amb}} + 9\times10^{11} \frac{\alpha I_{amp}}{r_o \omega_p(r_o)} \frac{1}{2} \ln \frac{n_o}{n_{amb}} \tag{12}$$

with r_o in cm and ω_p in sec^{-1}. The resistive contribution to the impedance is

$$Z = 9\times10^{11} \frac{\alpha}{r_o \omega_p(r_o)} \frac{1}{2} \ln \frac{n_o}{n_{amb}} \text{ ohms} \tag{13}$$

The hollow cathode,[7] operating in the spot mode at a flow rate of 100 mA equivalent, produced an electron density of about 10^{12} cm^{-3} at about 1 cm from the orifice. Taking $r_o = 1$ cm, $n_o = 10^{12}$ cm^{-3}, and $n_{amb} = 10^6$ cm^{-3},

$$Z = 23 \text{ ohms}$$

for $\alpha = 0.1$. Previous studies with this model required $\alpha \sim 0.1$, the value $\alpha = 1$ probably corresponds to an overestimate. The magnitudes of resistance given above with $\alpha \sim 0.1$ appear consistent with measurements made over the much shorter paths of current conduction involved in laboratory facilities.

Increasing the density n_o of the injected plasma by two orders of magnitude reduces R by a factor of ten. At densities greater than about 10^{12} cm^{-3} with $\theta \lesssim 1$ eV, classical scattering should be taken into account, however, since the mean free paths for Coulomb scattering are short ($\lesssim 1$ cm at $n = 10^{12}/cm^3$).

HOLLOW CATHODES AS ELECTRON COLLECTORS

A sphere whose diameter is much greater than a Debye length will collect an electron current greater than the plasma thermal current into the collector's area by attracting electrons across a space charge limited sheath. To collect a strongly enhanced current the potential on the sphere must be much larger than the plasma temperature, i.e., $e\phi \gg \theta$. The current voltage characteristic of such a configuration is well described by the theory of Langmuir and Blodgett.

Most descriptions of the passive collection of electrons by the tethered satellite are based upon space charge limited sheath theory with some modifications due to magnetic field and presheath effects.[12-14] The theory presented here addresses the changes in the potential structure that occur when a plasma is generated in the vicinity of the sphere. This theory omits the effect of a magnetic field, an omission not totally justified, especially in regions where the electron cyclotron frequency is comparable to or greater than the local plasma frequency.

There is little data on the use of hollow cathode plasma sources to enhance electron collection. Theoretical considerations, however, support what limited data there is: the effective impedance of an electron collecting probe is greatly reduced by copious emission of plasma. Even though the theory is incomplete, it identifies the regimes of impedance reduction and defines values of the plasma generation rate which will produce substantial changes in the impedance. Increasing the plasma generation rate, I_p, first reduces the voltage drop across the space charge limited collection sheath, further increases collapse the space charge sheath, and, when the ion generation rate is increased beyond the electron collection rate I_e, current is transported by the ions.

In fact the different regimes of current collection may be categorized according to the following inequalities between ion generation rate I_p and electron collection rate I_e:

Regime I:

$$I_p < \sqrt{\frac{m_e}{m_i}}\, I_e$$

Regime II:

$$\sqrt{\frac{m_e}{m_i}}\, I_e < I_p < I_e$$

Regime III:

$$I_p > I_e$$

Each of these regimes is considered below. For convenience, the collecting sphere is assumed to operate at a constant current.

Regime I.

For a null ion generation rate, current collection (B = 0) is well understood and requires large voltages to extract current much in excess of the geometrical limit. The effect of generating a small amount of plasma at the sphere is approximately equivalent to emitting ions from the anode of a diode. The effect of the electrons created in the ionization process can be ignored if the rate of plasma production is much less than the collected electron current. The plasma ions stream out across the sheath, cancelling a portion of the electron space charge. For planar diodes it has been shown[15] that the maximum ion current density that the sheath can extract is related to the electron current density by

$$j_i = \sqrt{m_e/m_i}\; j_e \,. \tag{14}$$

This relation, known as the "Langmuir condition", is also the basic stability condition for a strong plasma double layer. At this ion current, the voltage required to sustain a fixed electron current is reduced by one-third. For nonplanar geometries this current ratio can be exceeded by factors of order two. The resulting small reduction in sheath voltage is of little importance compared with the dramatic change that occurs when the plasma generation rate increases beyond the j_i of the double layer stability condition which separates regimes I and II.

Regime II.

Recent calculations of the effect of ionization in electron collecting sheaths have shown that when the "Langmuir condition" ion current is exceeded, the generated plasma remains quasineutral and the ions expand hydrodynamically.[16] In the limit of the plasma generation rate large compared with the "Langmuir condition" ion current, and assuming constant temperature, the potential profile can be described by the Boltzmann law, Eq. (5). The ion density is determined by the self-consistent motion in the quasineutral field. The resultant description of the potentials and densities is the same as that for hollow cathode neutralizers used as electron emitters. What is not certain is the magnitude of the electron transport coefficients. The model described in the previous section for electron emission can serve as a first estimate of electron collection from the ambient plasma. From Eq. (13) the collection area enhancement possible while maintaining isothermal quasineutrality can be obtained by substituting for the total current in terms of the ambient thermal current times an effective collection area, i.e.,

$$I = j_o \, 4\pi R^2. \tag{15}$$

For a collector radius, a, of one meter, this estimated collector area exceeds the geometric area by the factor

$$\frac{R^2}{a^2} = \frac{r_o^2}{a^2} \frac{n_o}{n_{amb}}$$

Taking r_o = 1 cm, and $n_o/n_{amb} = 10^6$

$$\frac{R^2}{a^2} = 100$$

Further study is necessary to determine the accuracy of this collection area enhancement.

The plasma generation rate required to sustain this lower impedance mode of electron collection can be estimated as follows. At the effective collection radius R defined by Eq. (15), the ion current from the plasma source is

$$I_i = 4\pi R^2 j_i = 4\pi R^2 n_i V_i ,$$

and since $n_i \simeq n_e$, where n_e is the ambient density

$$I_i = 4\pi R^2 n_e V_i = I_e \frac{V_i}{V_e}$$

where V_e is the thermal speed of ambient electrons and V_i is the speed of source ions at the effective collection radius R. As indicated schematically in Figure 3, the net movement of ions is down the potential hill separating the collector from the ambient plasma.

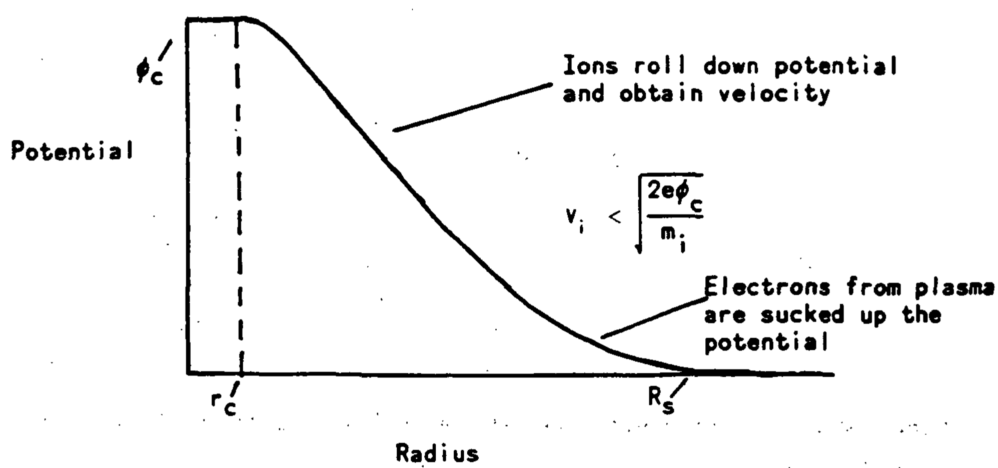

Figure 3. Potential profile around the plasma source.

Neglecting the effect of drag, ions starting from rest would attain the maximum velocity $(2e\ \phi_c/m_i)^{1/2}$, so that

$$I_p < I_e(m_e e\phi_c/m_i\theta)^{1/2}$$

and the bound on the required ion current varies only as the square root of the potential. From Eq. (12) and the discussion following it, electron currents near one ampere would correspond to potentials ϕ_c ~10 volts. For an argon plasma, with $\sqrt{m_i/m_e}$ ~300, and for θ ~0.1 eV

$$I_p \lesssim \frac{I_e}{30}$$

Regime III.

For plasma generation rates in excess of the collected currents the net electron current is outward from the subsatellite. In this case the ions transport the current and the effective mobility of the electrons plays little role in determining the plasma potential, provided that the current does not exceed the net rate of escape of ions I_1 from the vicinity of the collector. Thus, assuming full ionization of the neutral gas flow through the cathode, the required mass flow rate for ion transport is

$$I_1 \lesssim I_p = \frac{\dot{m}q}{Am_H} = 10^5 \frac{\dot{m}}{A} \text{ ampere}$$

where $\dot{m}$ is the mass flow rate in grams/sec of atoms of atomic weight A and m_H is the proton mass. Of course, if the cathode does not float with respect to the collector, the total current through the cathode may exceed I_1, but any current through the cathode-collector-plasma loop does not flow through the tether. It is useful to observe that $I_p \simeq 1$ ampere corresponds to a flow rate slightly less than A grams per day. Since high ionization efficiencies are achievable with hollow cathode sources operating in their spot modes it is unlikely that such flow rates for the duration of TSS-1 would significantly impact the satellite mass.

CONCLUSION

For both the electron emitting and electron collecting ends of the tethered satellite system, locally generated plasmas eliminate the space charge sheath. The high voltages necessary to transport charge across a space charge sheath makes the sheath regions the highest impedance portions of the tether system. Reducing this impedance by local plasma sources, such as hollow cathodes, will greatly enhance the effectiveness of a tethered satellite system. While parts of the theory are not yet fully developed and magnetic fields have not been included, the theory does provide a framework for understanding how currents flow through the locally generated plasmas. The theory predicts the impedance for electron emission from the orbiter as a function of plasma generation rate, I_{plasma}; tether current, I_{tether}; and ambient plasma density. For electron collection by the subsatellite, the theory predicts three different collection regimes:

I. $I_{plasma} < \sqrt{\frac{m_e}{m_i}}\, I_{tether}$, High impedance space charge limited collection

II. $\sqrt{\frac{m_e}{m_i}}\, I_{tether} < I_{plasma} < I_{tether}$, Resistive quasineutral transport of electrons

III. $I_{tether} < I_{plasma}$, Low impedance ion transport

Electron emission and all modes of electron collection are well within the capabilities of present technology hollow cathode plasma sources. Regime II is of primary interest, permitting low impedance electron collection for low plasma production rates. For a plasma emitted into the ionosphere in low earth orbit the ion production rate I_p required to extract a current I_e from the ambient plasmas satisfies $I_p \lesssim I_e/30$.

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SECOND BIENNIAL WORKSHOP
APPLICATIONS OF TETHERS IN SPACE

VENICE, ITALY

OCTOBER 15-17, 1985

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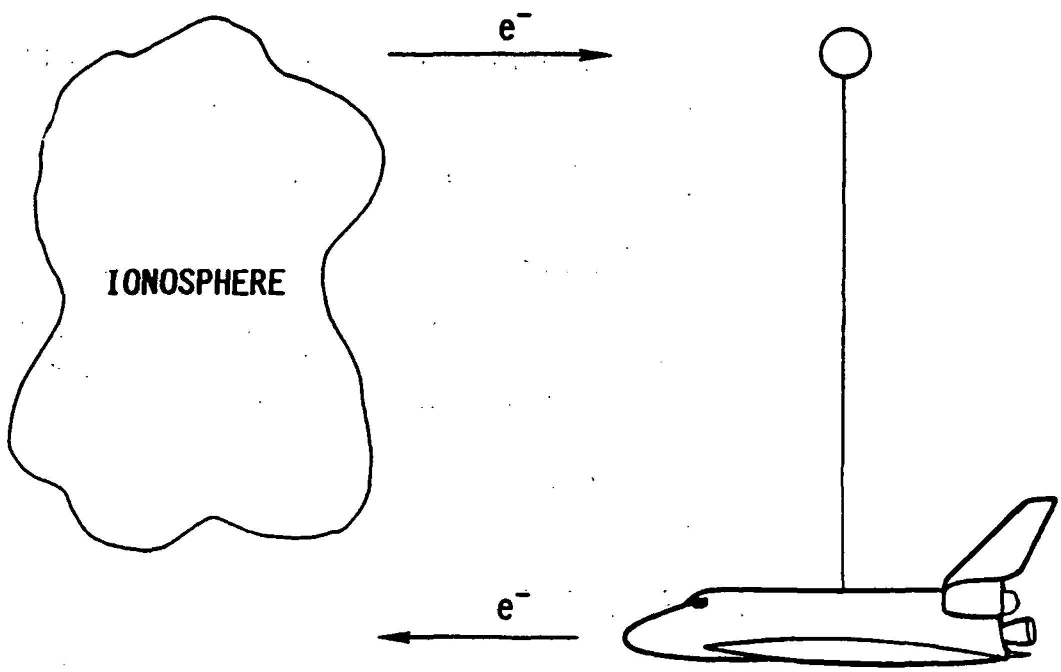
BASIC REQUIREMENTS FOR TSS GENERATOR

- LOW IMPEDANCE ELECTRON COLLECTION BY TETHERED SATELLITE
- LOW IMPEDANCE ELECTRON EMISSION FROM SHUTTLE
- CONTROL OF SHUTTLE GROUND

ELECTRODYNAMIC TETHER CIRCUIT



Transport of electrons to subsatellite and from orbiter determine the magnitude of the tether current.

HIGH VOLTAGE ARCING

- Solar arrays always arc at high negative potentials

- Have caused disruption of power supplies

- This has been demonstrated both in

Lab Experiments	Year	Voltage
Kennerud - Boeing	1974	-1000 V
Chaky - TRW	1983	-1000 V
Snyder - NASA/LeRC	1984	-600 V

Many others

Space Flights

Space Flights		
PIX I and II		-250 - 1000 V

- Arcing is not restricted to solar arrays

SPACE DATA ON ELECTRON COLLECTION

- PIX II 2000 cm^2 $V_{max} = 1000$ Volts $Z_{eff} \cong 300{,}000\,\Omega$

  $n_e = 10^4$ $I_{max} = 3$ ma
  (800 km)

- SPACELAB I 68 m^2 $V_{max} \cong 1000$ Volts $Z_{eff} \cong 10{,}000\,\Omega$

  $n_e \sim 10^5$ $I_{max} \cong 100$ ma

- For shuttle altitudes and above, classical collection appears valid

HOW WELL DO OTHER CONTACTORS WORK

- ELECTRON GUN EMITTER

  PERVEANCE = 6×10^{-6} amp/volt$^{3/2}$

  FOR 1 AMPERE

  V = 3000 volts

  $Z_{eff} \cong 3000$ ohms

- PASSIVE 1.5 METER SPHERE COLLECTOR

  SPACE CHARGE LIMITED, $n_e = 10^6$

  $V_{sat} = 2500$ volts

  $Z_{eff} \cong 2500$ ohms

  with magnetic field, $Z_{eff} \cong 6000$ ohms

  SPACE CHARGE LIMITED, $n_e = 10^5$,

  $Z_{eff} \cong 8000$ ohms

  with magnetic field, $Z_{eff} \cong 50{,}000$ ohms

PREVIEW OF IMPORTANT RESULTS USING PLASMA SOURCES

- LOW IMPEDANCE HIGH CURRENT ELECTRON EMISSION
  - TENS OF OHMS
- LOW IMPEDANCE ELECTRON COLLECTION
  - $I_e \sim 30\ I_p$
- LOW MASS FLOW REQUIREMENTS
  - 1 AMP ELECTRON COLLECTION REQUIRES ~1 gm/day ARGON PLASMA GENERATION RATE

IMPORTANCE OF PLASMA CONTACTORS
FOR
ELECTRODYNAMIC TETHERS

- INCREASE CURRENTS DRIVEN IN IONOSPHERE
- FEASIBILITY OF SPACE POWER SYSTEMS
- TEST NEUTRALIZATION OF SPACECRAFT FOR CHARGED PARTICLE BEAM EMISSION

THEORY OF PLASMA CONTACTORS

- Collision lengths very long, debye lengths very short. Plasma dominated by collective effects.

- Experiments suggest the plasma is turbulent.

OUR APPROACH

- Fluid model

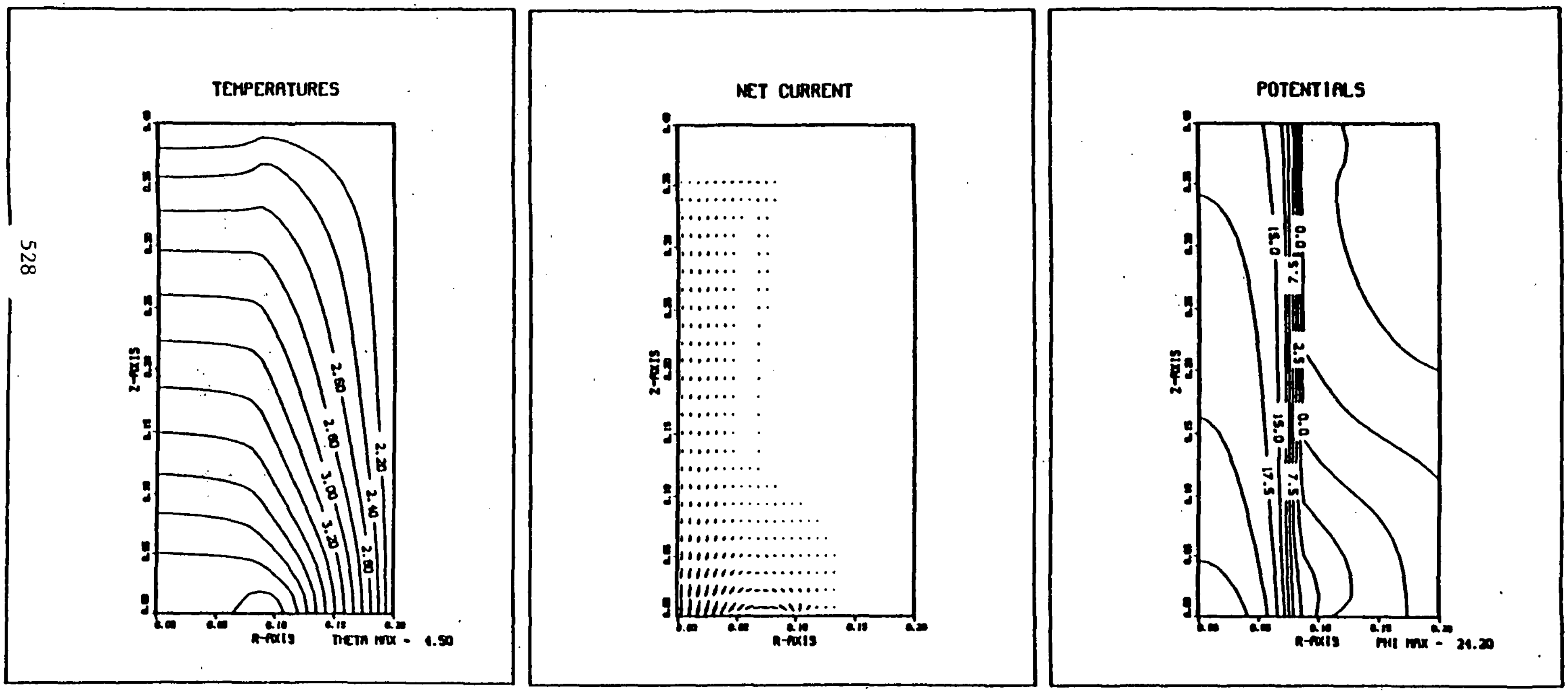
  -- Continuity, momentum, and energy equations

- $\nu_{eff} \simeq f_p$ from electron 2-stream instability

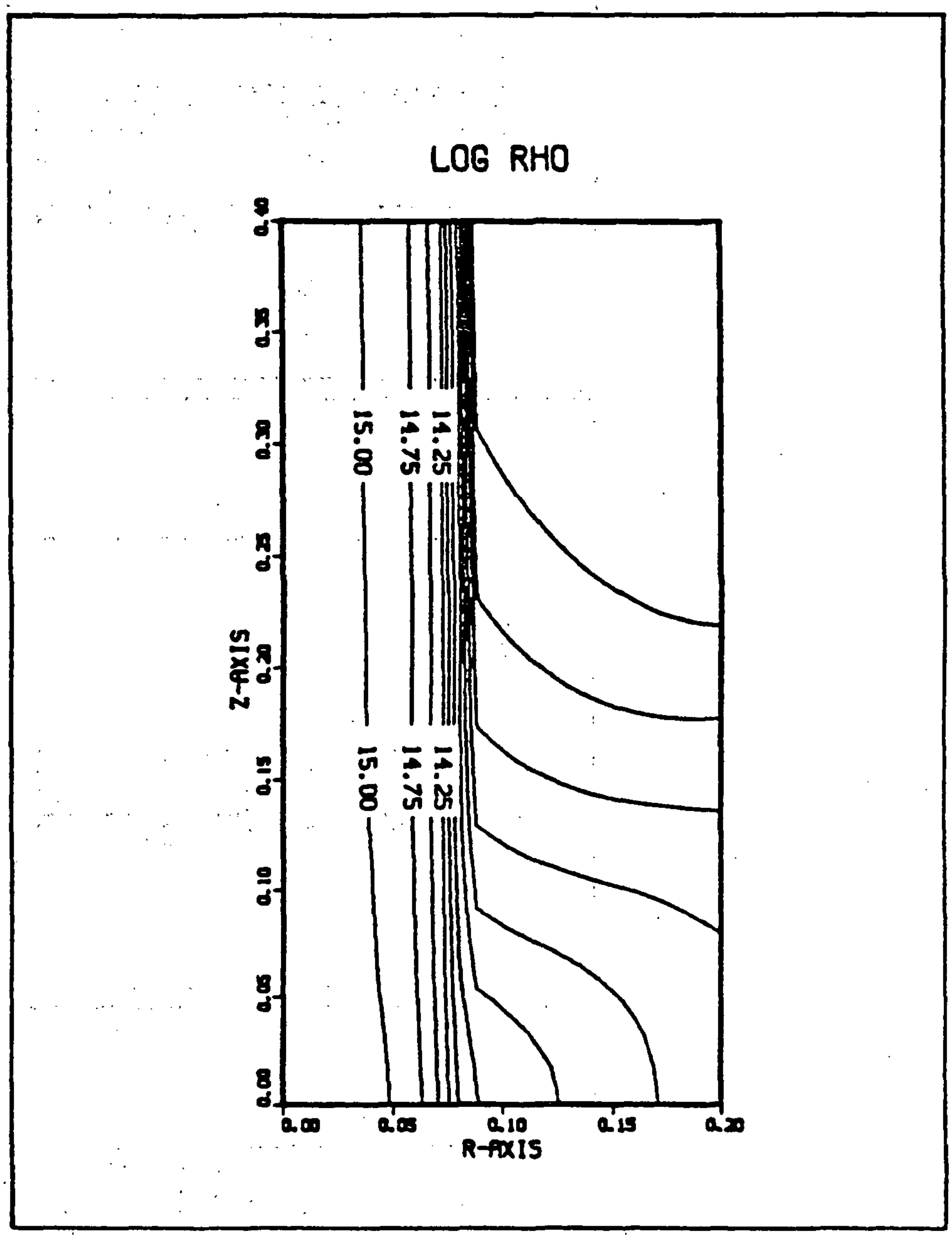
SERT II RESULTS

CHARGE EXCHANGE CURRENT	0.9 mA
PEAK PLASMA DENSITY	$2 \times 10^{15}\ m^{-3}$

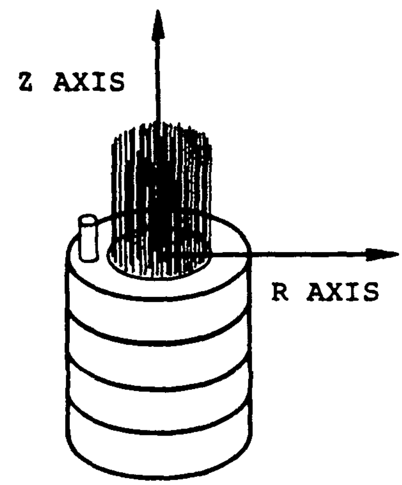
Neutralizer Position	Thermal Boundary Condition 2 eV	Insulating Thermal Boundary
0.08	θ_{max} = 2.3 eV ϕ_{max} = 13.8 V	θ_{max} = 4.1 eV ϕ_{max} = 21.3 V
0.10	θ_{max} = 2.4 eV ϕ_{max} = 14.7 V	θ_{max} = 4.5 eV ϕ_{max} = 24.2 V



Temperature, Current Density, and Potentials for SERT II Case: Insulating Orifice Plate; 10 cm Neutralizer Radius.



Logarithmic plasma density (beam plus charge exchange ions) for SERT II thruster cases. (Contour labels are common logarithm of density in m^{-3}.)



PARAMETERS FOR THE SERT II THRUSTER

BEAM CURRENT	0.085 A
NEUTRAL EFFLUX	0.055 A
NEUTRAL TEMPERATURE	0.06 eV
AMBIENT TEMPERATURE	2 eV
BEAM ENERGY	3 keV
BEAM RADIUS	0.07 m
QUADRATIC BEAM PROFILE	
NEUTRALIZER RADIUS	0.08 m; 0.10 m

ION BEAM NEUTRALIZATION CODE

- 2-D R-Z Geometry

- Finite element with fancy numerics

- Code requires as input

  -- Ion currents

  -- Ion densities

  -- Boundary conditions on:

  Electron currents

  Electron temperatures

- Code predicts

  -- Electron temperatures

  -- Electron potentials

  -- Net currents

CONSERVATION EQUATIONS FOR BULK PLASMA

- Particle Conservation

$$\left.\nabla \bullet N\vec{V} = 0\right\} \text{ions}$$

$$\left.\begin{aligned} \vec{\nabla} \bullet j &= 0 \\ \vec{j} &= ne(\vec{V} - \vec{V}_e) \end{aligned}\right\} \text{electrons plus ions}$$

- Neutrality

$$n = N$$

- Electron Momentum

$$\nabla p + en\vec{E} = \eta ne\vec{j}$$

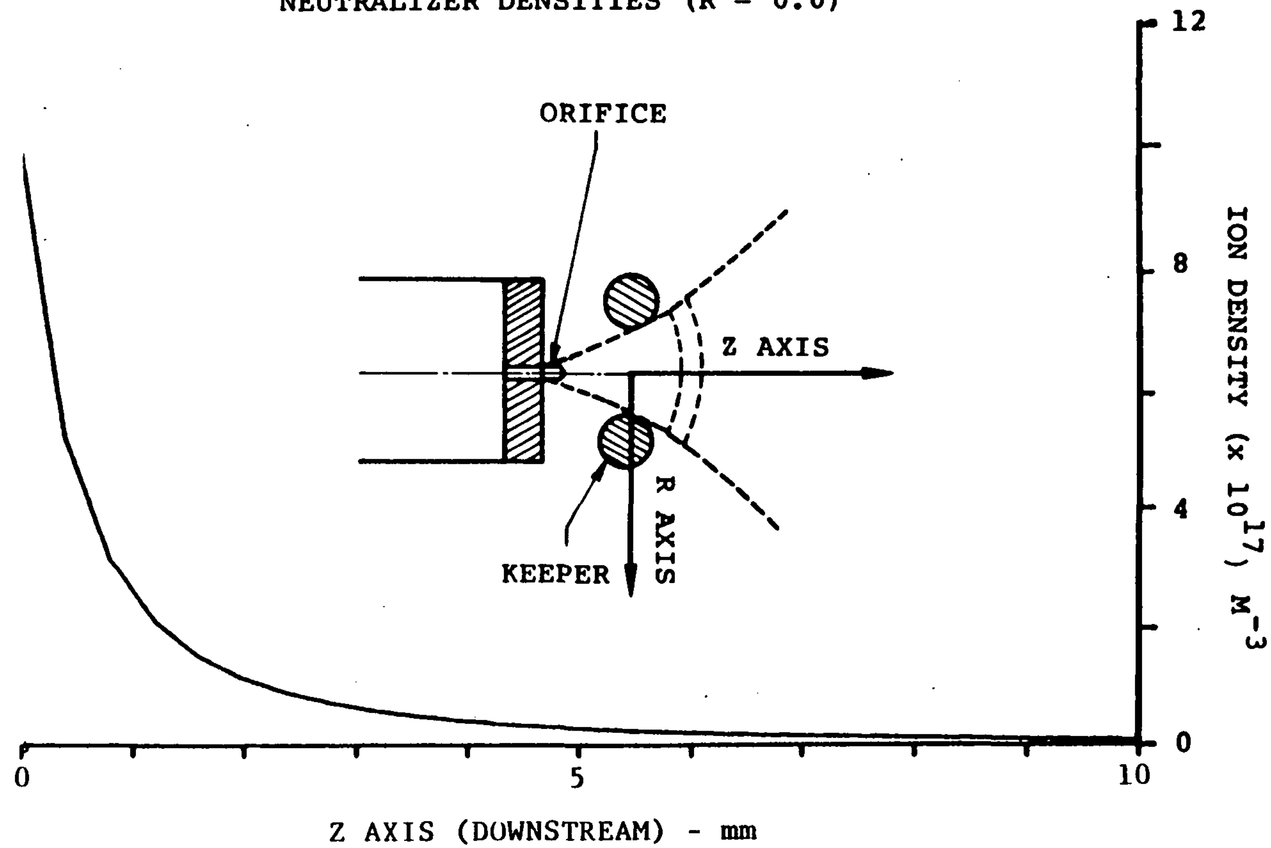
$$\eta^{-1} = \frac{\omega_p^2}{4\pi} \nu^{-1}$$

- Electron Energy

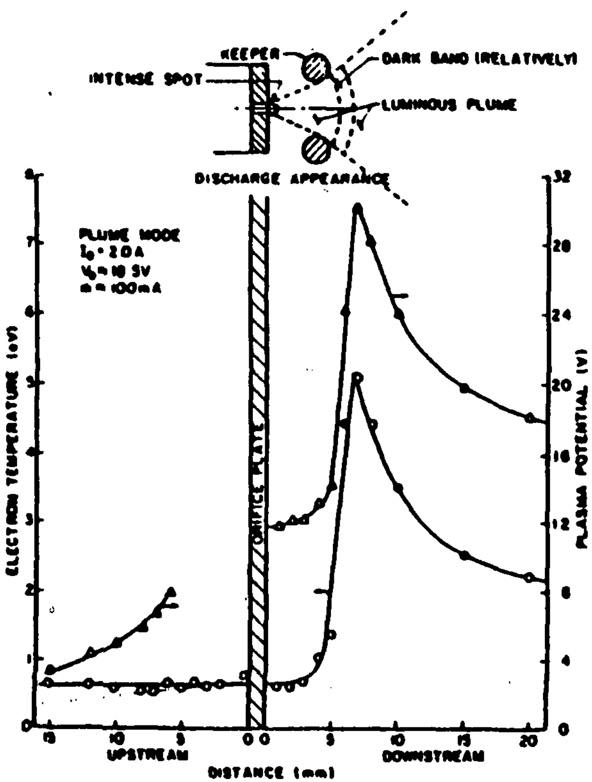
$$-\nabla \bullet \kappa\nabla\theta = \eta j^2$$

$$\kappa = \frac{3}{2} \eta^{-1} \left(\frac{k^2}{e}\right) \theta$$

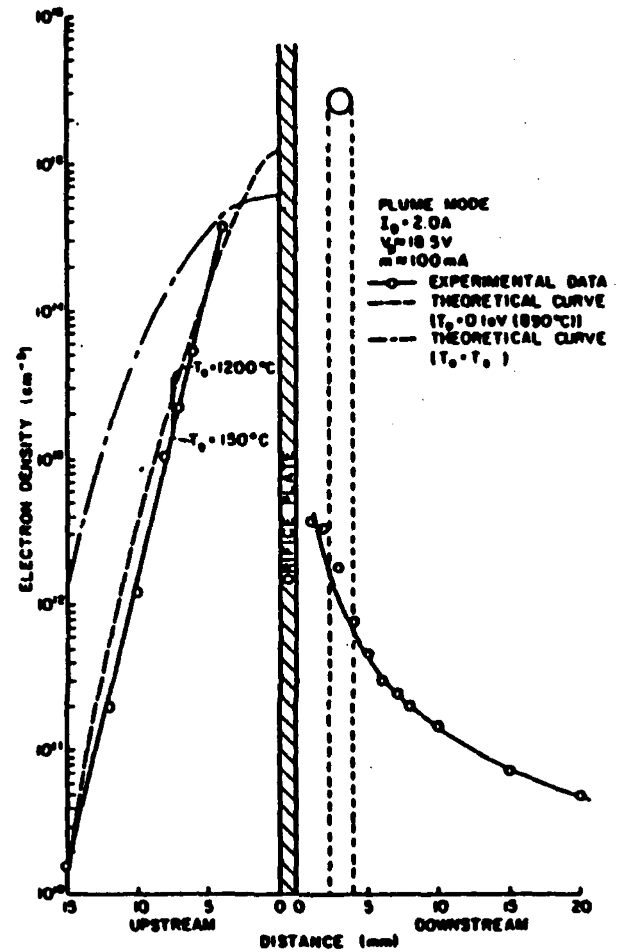
NEUTRALIZER DENSITIES (R = 0.0)



AN INVESTIGATION OF MERCURY HOLLOW CATHODE PHENOMENA



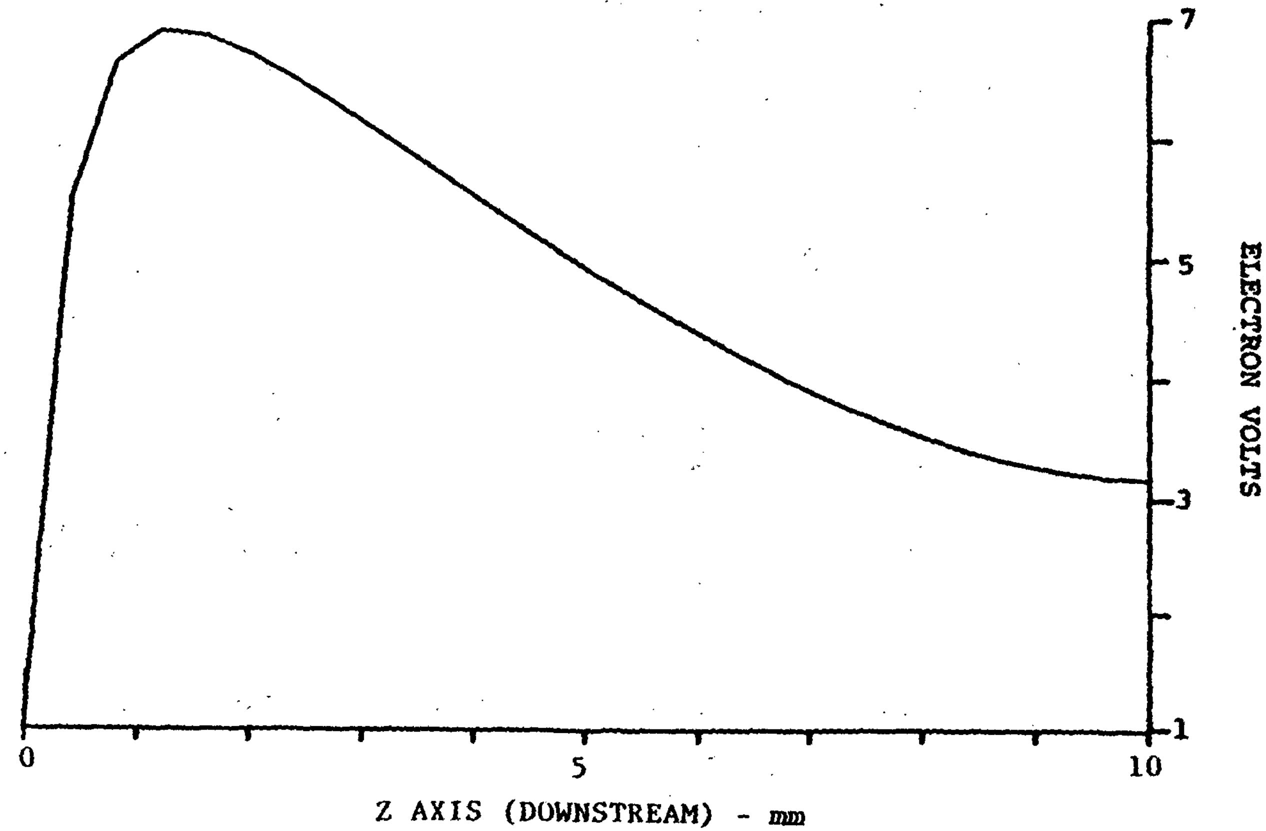
Cathode plasma potential and electron temperature profiles--plume mode.



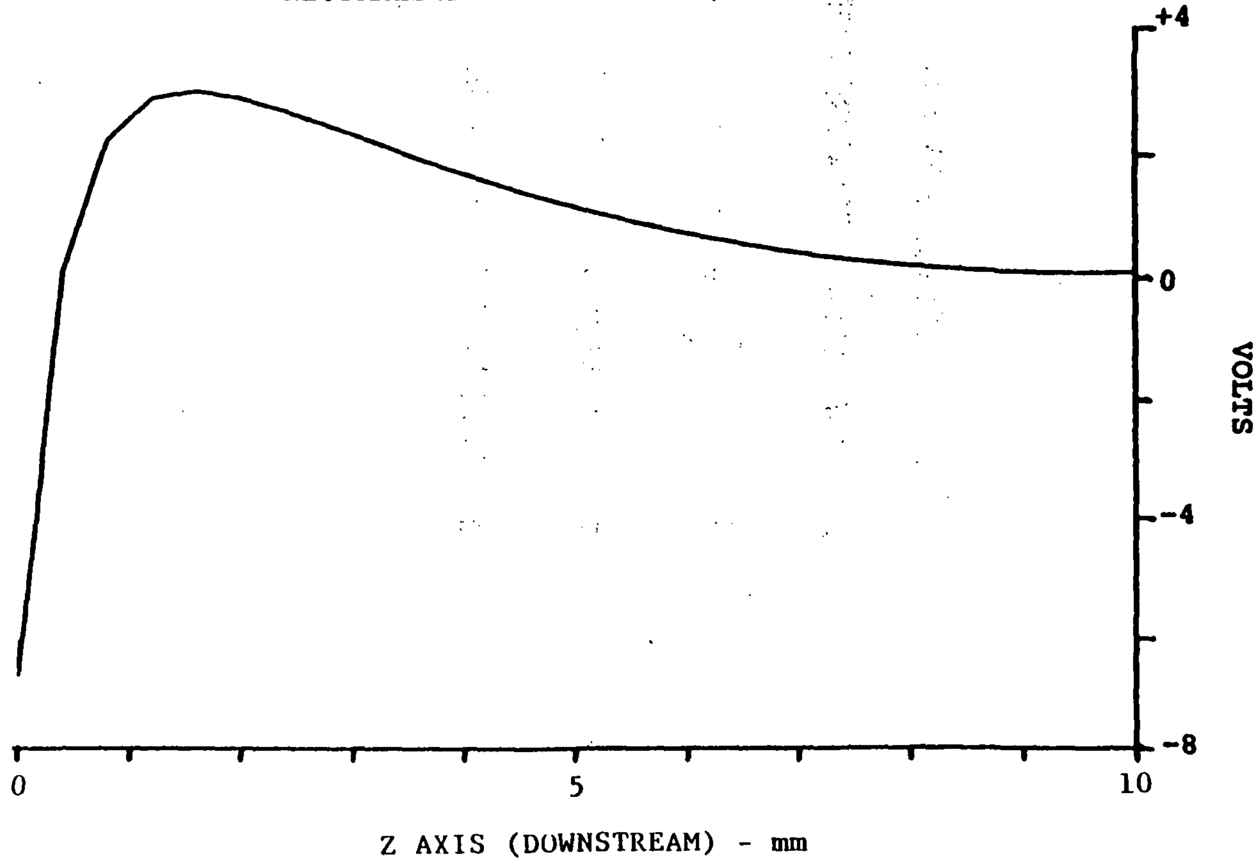
Cathode electron density profiles--plume mode.

(D. E. Siegfried and P. J. Wilbur,
Colorado State University,
Fort Collins, CO)

NEUTRALIZER TEMPERATURES (R = 0.0)



NEUTRALIZER POTENTIALS (R = 0.0)



RESISTIVITY MODEL

- BASED UPON LITERATURE EXAMPLES
- $\nu \rightarrow \frac{\omega_P}{2\pi}$ when $j/j_{th} \sim 1$
- $\nu \rightarrow$ CLASSICAL $j/j_{th} << 1$
- INTERMEDIATE ION ACOUSTIC

FORMULATION:

$$\sigma = \varepsilon_0 \omega_p / (\nu/\omega_p)$$

where

$$\nu/\omega_p = 10^{-13}\, n^{1/2}\, \lambda_c\, \theta^{-3/2} \qquad \text{(Classical)}$$

$$+ \alpha_1\, e^{-\beta_1 j\,th/j} \qquad \text{(e - e)}$$

$$+ 2\alpha_2 (m_e/m_i)\, e^{-\beta_2 (n_e/j)\sqrt{e\theta/m_i}} \qquad \text{(Ion-Acoustic)}$$

$$+ \frac{\alpha_3}{2\pi}\left(\frac{m_e}{m_i}\right)^{1/3} e^{-\beta_2 j\,th/j} \qquad \text{(Buneman)}$$

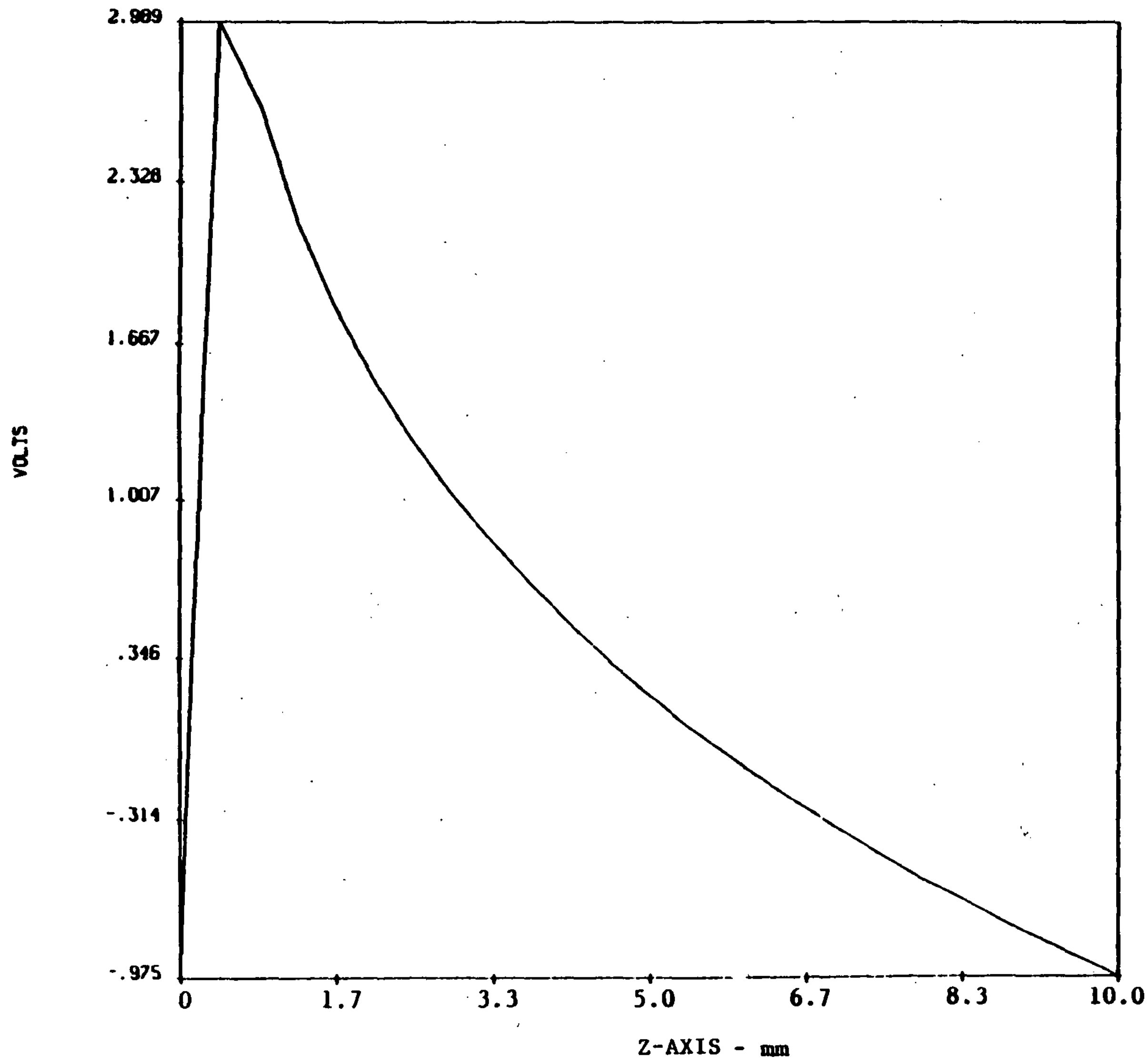
$\alpha_1 = 0.08;\ \beta_1 = 1$

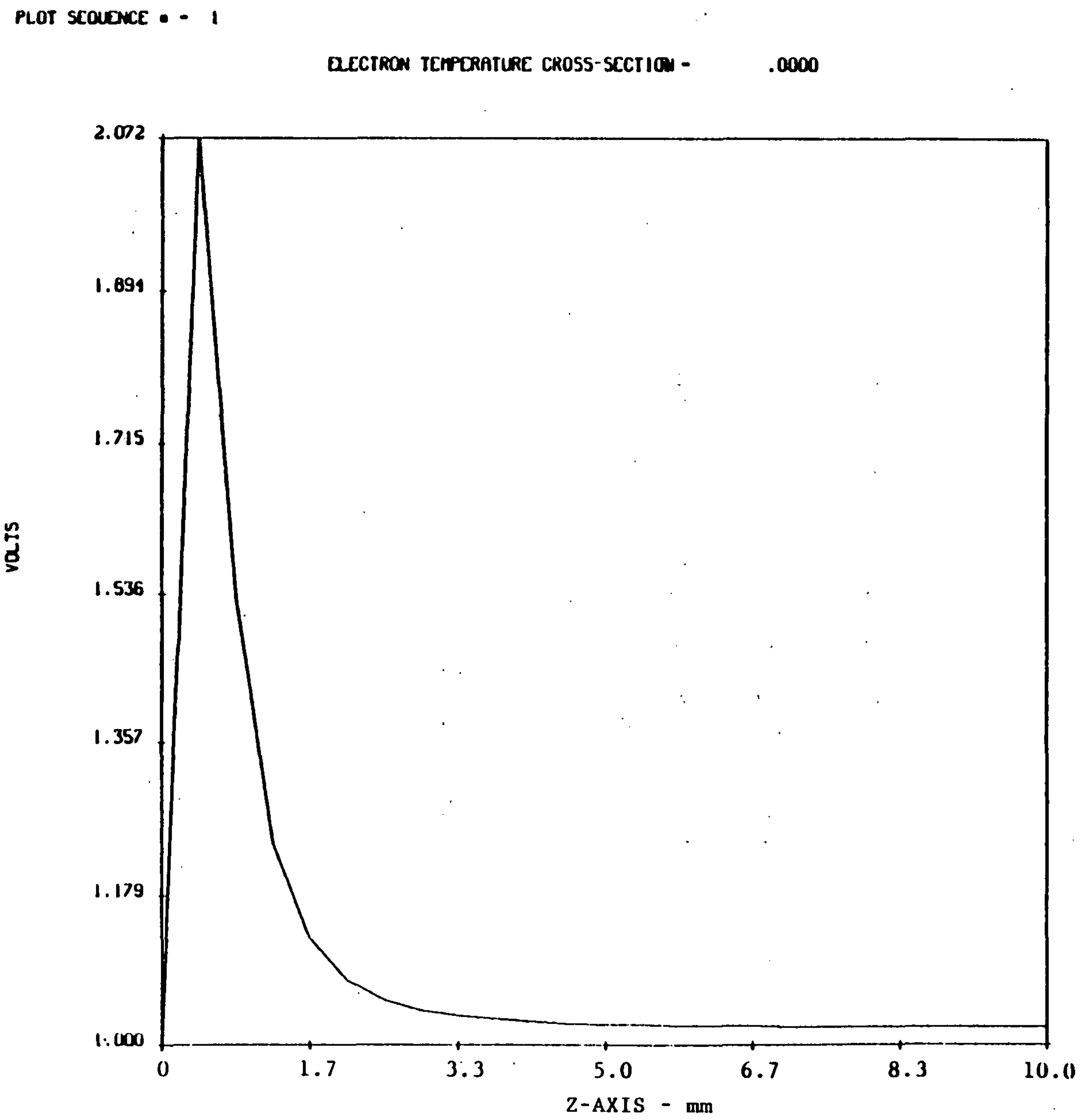
$\alpha_2 = \alpha_3 = 1$

$\beta_2 = \beta_3 = 1$

PLOT SEQUENCE = - 1

POTENTIAL CROSS-SECTION R - .0000




PLOT SEQUENCE # - 1
ELECTRON TEMPERATURE CROSS-SECTION - .0000
VOLTS
2.072
1.894
1.715
1.536
1.357
1.179
1.000
0
1.7
3.3
5.0
6.7
8.3
10.0
Z-AXIS - mm

PLASMA SOURCE AS ELECTRON EMITTER

- LOCATED ON SHUTTLE
- FLUID MODEL OF ELECTRON TRANSPORT FROM ION THRUSTER NEUTRALIZATION STUDIES

  $$\nu_e \cong 0.1\ \omega_p$$

- $Z_{eff} \cong 20$ ohms

APPROXIMATION FOR PRESCRIBED DENSITY AND CONSTANT ELECTRON TEMPERATURE

$$n = \frac{n_o\, r_o^2}{r^2}$$

$$R = r_o \left(\frac{n_o}{n_{amb}} \right)^{1/2}$$

$$\theta\, \nabla n - ne\, \nabla \phi = \eta ne \frac{I}{4\pi r^2}$$

$$- \frac{\theta}{e} \ln \frac{n_o}{n_{amb}} + \phi(r_o) = \frac{I}{4\pi} \int_{r_o}^{R} \eta(r) \frac{dr}{r^2}$$

$$\phi_o(r_o) = \theta \ln \frac{n_o}{n_{amb}} + 9 \times 10^{11} \frac{\alpha I_{amp}}{r_o \omega_p(r_o)} \frac{1}{2} \ln \frac{n_o}{n_{amb}}$$

$$\alpha \approx 0.1$$

PLASMA SOURCE AS ELECTRON COLLECTOR

- LOW ION GENERATION RATE,

$$I_P < \sqrt{\frac{m_e}{m_i}}\ I_e$$

  - BIPOLAR SPACE CHARGE SHEATH
  - INCREASES I_e BY ~ 2

- MODERATE ION GENERATION RATE,

$$\sqrt{\frac{m_e}{m_i}}\ I_e < I_p < I_e$$

  - QUASINEUTRAL WITH ELECTRON TRANSPORT
  - FLUID MODEL PREDICTS 10-1000Ω IMPEDANCE

- HIGH ION GENERATION RATE,

$$I_p > I_e$$

  - QUASINEUTRAL WITH ION TRANSPORT
  - $\dot{m} \simeq$ A GRAMS/DAY AMPERE

PLASMA SOURCE AS ELECTRON COLLECTOR

- LOCATED ON SUBSATELLITE
- THREE MODES OF OPERATION DEPENDENT UPON PLASMA GENERATION RATE
- ALL WILL LOWER SHEATH IMPEDANCE

PLASMA SOURCE REQUIREMENTS FOR ELECTRON COLLECTION

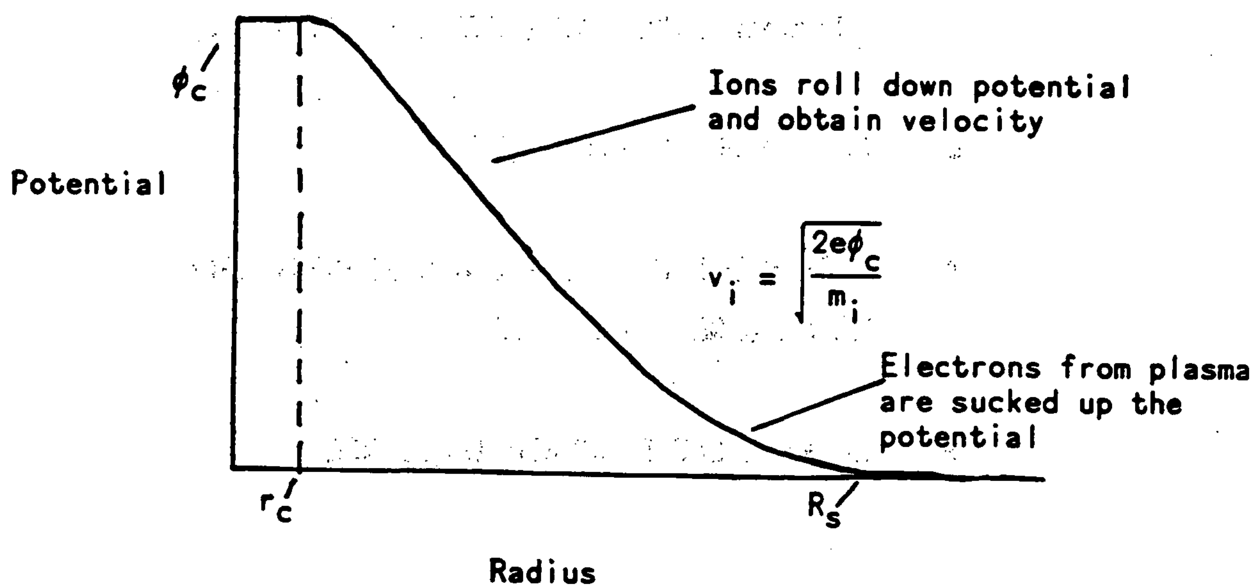
Given: $I_e \equiv$ electron current required

$\theta \equiv$ ambient plasma density and temperature

Theory States: $n_p = n_a$ on effective sheath, R_s, surface to maintain low potentials

For Spherical Collection:

$$I_e = 4\pi R_s^2 j_a = 4\pi R_s^2 n_a v_e$$



r_c; $\phi_c \equiv$ collector radius, potential

$$I_p = 4\pi R_s^2 j_p = 4\pi R_s^2 n_p v_i$$

Using $n_p \doteq n_a$

$$\doteq 4\pi R_s^2 n_a v_i = I_e \frac{v_i}{v_e} = I_e \sqrt{\frac{m_e}{m_i} \cdot \frac{\phi_c}{\theta_e}}$$

$$I_p \doteq I_e/30 \text{ for } \phi_c \sim 10 \text{ V}, \theta_e \sim 0.1 \text{ eV}, \sqrt{\frac{m_i}{m_e}} \sim 300$$

SUMMARY

PLASMA CONTACTORS

- PROVEN LOW IMPEDANCE ELECTRON EMITTERS
- ENHANCE ELECTRON COLLECTION

  $-I_e \sim 30\ I_p$ FOR ARGON PLASMAS