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This report summarizes the results of a three year program devoted to theoretical and experimental research on plasma acceleration by Electron-Cyclotron-Resonance (ECR). Theoretical work in the first year of this effort centered on simple analytical treatment of many of the phenomena which have a role in ECR plasma acceleration. These analytical studies pointed out which phenomena are sufficiently important to be incorporated in the more rigorous theoretical studies of years two and three and also provided vital guidance to the process of designing the experimental apparatus. An experimental facility was developed in the first year of this program so that an ECR research device could be tested. The JPL facility has the unique capability of providing up to 20 kW of S-band microwave power and 18,000 liters/second of high quality vacuum system pumping for the study of advanced microwave propulsion concepts.

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ELECTRON-CYCLOTRON-RESONANCE PLASMA THRUSTER RESEARCH

FINAL REPORT
for the Period:
1 April 1987 through 31 March 1990

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and
Joel C. Sercel

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August, 1990

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SUMMARY

This report summarizes the results of a three year program devoted to theoretical and experimental research on plasma acceleration by Electron-Cyclotron-Resonance (ECR). Theoretical work in the first year of this effort centered on simple analytical treatments of many of the phenomena which have a role in ECR plasma acceleration. These analytical studies pointed out which phenomena are sufficiently important to be incorporated in the more rigorous theoretical studies of years two and three and also provided vital guidance to the process of designing the experimental apparatus. An experimental facility was developed in the first year of this program so that an ECR research device could be tested. The JPL facility has the unique capability of providing up to 20 kW of S-band microwave power and 18,000 liters/second of high quality vacuum system pumping for the study of advanced microwave propulsion concepts.

The Jet Propulsion Laboratory provided all of the equipment used to develop the facility at no cost to the AFOSR; we estimate that the value of this equipment is $250,000.00 not including the value (≈$500,000.00) of the microwave transmitter we are using. In the second year's effort, we began to use the new experimental apparatus to perform measurements of plasma beam density, electron temperature, accelerating potential, and accelerated ion energy distribution. We performed these measurements to provide a basis with which to test a quasi-one-dimensional steady-state model of ECR plasma acceleration which we also developed in the second year of this research program. The third year of this effort included activity in three distinct areas: i) the quasi-one dimensional steady-state model of ECR plasma acceleration was extended to included the effects of axial heat transport and finite vacuum system back pressure, ii) a simplified three-dimensional model of the plasma flow field was developed and used to calculate the shape of plasma stream lines in the device, and iii) additional experimental measurements where taken to further verify the theoretical models.

I. RESEARCH OBJECTIVES

The objective of this program has been to develop a quantitative scientific understanding of ECR plasma acceleration as it occurs in the ECR plasma thruster. The understanding obtained in this effort will be useful in developing the technology of practical ECR plasma thrusters. To accomplish this end, the first three years of this project have included both theoretical and experimental work. The theoretical work has centered on developing a model which treats several phenomena important in ECR plasma acceleration. This model has provided a framework within which experimental results can be understood. Experimental work is conducted in co-operation with the Jet Propulsion Laboratory using a full-scale (20 kW) laboratory apparatus provided by JPL and installed at the electric propulsion laboratory at JPL.

II. RESULTS AND STATUS OF RESEARCH

A. Theoretical Work

The theoretical aspect of this research consists of two separate modeling efforts. The first is a three-dimensional calculation to predict the plasma flow field of the ECR accelerator. The second, more extensive analytical effort, is the development of a quasi-one-dimensional three-component model which is used to understand non-equilibrium and radiation effects. Progress on each of these two efforts is outlined below.

1. Flow Field Model of Plasma Acceleration in a Magnetic Nozzle

The shape of plasma stream lines in the ECR plasma engine is important because excessive plasma beam divergence or failure of the plasma beam to detach from the magnetic field could reduce the propulsive efficiency of the device. In addition, a quantitative approach to predicting the effect of accelerator design on the shape of the plasma plume is needed to allow the development of practical ECR plasma engines. Additional motivation for this work is provided by technical issues associated with plasma detachment from the magnetic field in other advanced propulsion systems. We have developed an approach which may be useful in analyzing the detachment problem in some of these other systems.

We have used a collisionless, steady-state, cold plasma model to calculate the three dimensional flow field of the ECR plasma as it is accelerated through a diverging magnetic field. Our model, which is an extension of Kosmahl's model,[1] allows the calculation of the angle by which the plasma beam diverges during separation from the magnetic field. This divergence angle is important because the fraction of the momentum of the flowing plasma which is useful for thrust varies as the cosine of the divergence angle.

Our problem involves the acceleration of a plasma which is created at zero velocity via ionization of a gas at a specified position in a cylindrical coordinate system. An applied diverging magnetic field is assumed to emanate from a collection of current loops located perpendicular to, and centered on, the z-axis of the coordinate system. Although random thermal energy effects are neglected in the cold plasma approximation, the energy associated with electron Larmor motion perpendicular to magnetic field lines is treated in the present model and constitutes an important effect of the plasma's thermal energy. This electron Larmor motion produces a finite diamagnetism in the plasma. By symmetry, the azimuthal components of the magnetic field of a current loop or a collection of radially concentric current loops is zero and the gradient of such a field has only radial and axial components. The grad-**B** drift caused by the electron Larmor motion produces an azimuthal electron current which must be included in the initial conditions.

The only forces initially available to accelerate the plasma are the Lorentz force associated with azimuthal currents and the diamagnetic body force. The azimuthal component of these body forces is zero. The plasma is therefore accelerated only radially and axially. No external torques are applied to the plasma. The resulting radial and axial plasma velocity can induce azimuthal current. As stated above, azimuthal current in this arrangement induces radial and axial forces. Because no mechanism is present to provide net azimuthal body forces and associated azimuthal plasma velocity, there is no induced radial or axial current. The absence of radial and axial currents significantly simplify our analysis.

Based on these assumptions, we have derived a set of equations which can be used to predict the details of the flow field for the ECR plasma accelerator.[2] These equations can be expressed as a set of eight first order ordinary differential equations. We have used this set of equations to model the plasma flow field of the accelerator we are presently testing experimentally.[3,4] For this calculation we approximate the magnet coil as a single-turn current loop. The radius of the current loop is taken to be 0.2 meters and the total current in the solenoid is taken to be 2.5×10^4 Amperes.

Plasma stream lines were calculated for plasma elements starting at eleven initial positions relative to the center-line of the magnet coil. For each of the eleven cases, the initial value of z was specified to be 0.05 m. Initial values of r were varied between r=0.005 m and r=0.05 m inclusively. The initial value of $\dot{r}$ was taken to be zero, while the initial value of $\dot{z}$ was taken to be 100 m/s. The atomic mass of the ions was 40 amu, representative of argon. The magnetic moment of the spiralling electrons was calculated based on an assumed mean energy per electron of 200 eV. This energy level was chosen to yield a specific impulse of approximately 3000s (30,000 N•m/s).

Fig. 1 and Fig. 2 show the results of these calculations. Fig. 1 depicts the calculated trajectories in terms of radial position as a function of axial position for plasma elements initiating from eleven different locations. Calculated magnetic field lines are shown as dotted lines. Fig. 1 clearly indicates that the plasma crosses the magnetic field lines at a large angle. Fig. 1 also shows that the plasma divergence for our research device is very large and that most of the separation from the magnetic field occurs two to five meters from the accelerator. Conservation of mass can be used to show that in the region of separation, the plasma density has dropped by four to five orders of magnitude relative to the plasma density at the source of the plasma flow. This result suggests that effective performance testing of ECR plasma engines may require the use of vacuum facilities with very large pumping capacities and radii of up to five meters.

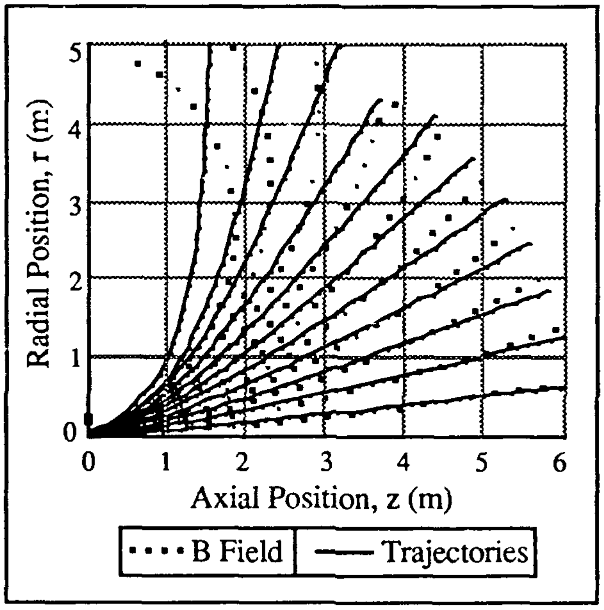

Fig. 1 Calculated plasma stream lines for eleven initial positions.

Fig. 2 shows the time variation of the radial and axial components of the plasma velocity for two specific initial positions. In Fig. 2a the plasma element has an initial radial coordinate of r=0.005m. In Fig. 2b the plasma element has an initial radial coordinate of r=0.01m. Fig. 2a and Fig. 2b both show that the radial and axial components of the plasma velocities effectively approach a constant value in a time period of less than about 10^{-3} s. This asymptotic behavior of the plasma velocity further supports the conclusion that the plasma completely separates from the field of the magnetic nozzle.

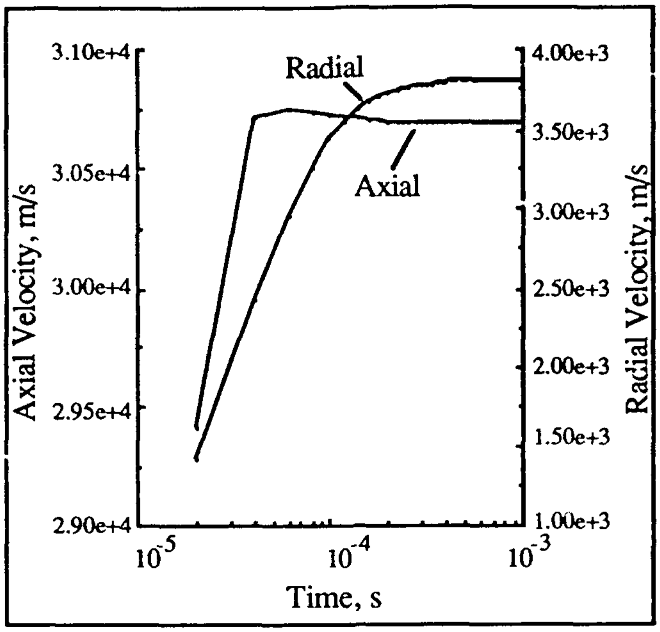

Fig. 2a Axial and radial plasma velocity as a function of time for a plasma element with initial radial position 0.5 cm from the accelerator axis and an initial axial position 5.0 cm from the center-line of the magnet coil.

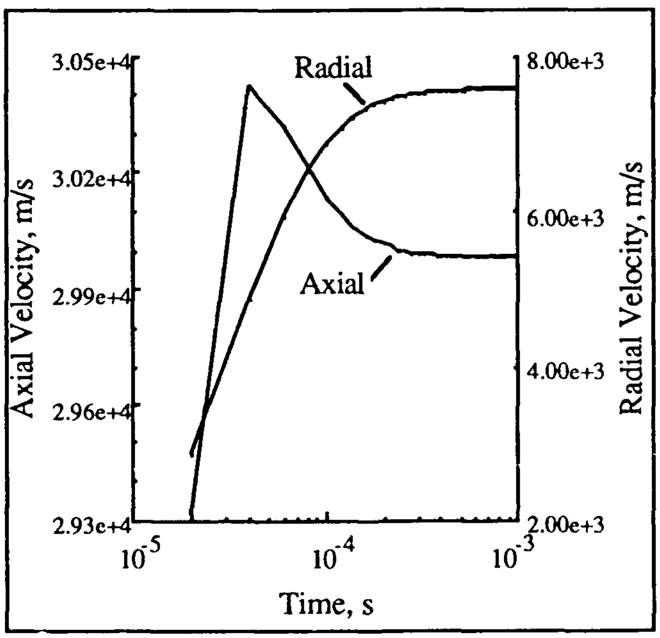

Fig. 2b Axial and radial plasma velocity as a function of time for a plasma element with initial radial position 1.0 cm from the accelerator axis and an initial axial position 5.0 cm from the center-line of the magnet coil.

In both Fig. 2a and Fig. 2b, the initial rate of acceleration of the plasma is approximately 1.5×10^9 m/s, corresponding to a space-charge induced ambipolar electric field of about 625 V/m. For the conditions of Fig. 2a and Fig. 2b, the axial component of the plasma velocity is always much larger than the radial component of the plasma velocity. This fortuitous result is, however, not always obtained. For example, several of the trajectories depicted in Fig. 1 display radial velocity components greater than axial velocity components after separation from the magnetic field. Calculated propulsive energy loss due to azimuthal motion of ions and electrons was found to be less than 2 percent in all cases studied.

Our calculations support Kosmahl's observation that the plasma divergence angle (and hence the divergence loss) is strongly dependant on the ratio of the radius of the magnet coil to the distance between the center line of the accelerator and the initial radial position of the plasma element. For a fixed coil radius, plasma which originates near the center line of the accelerator tends to separate from the magnetic field with minimal divergence, while plasma which originates at a larger radial position tends to diverge strongly. Coils with larger radii can be expected to produces less divergent plasma beams.

These calculations also show that in the region of plasma separation from the magnetic field, the vast majority of the energy initially available in the electron Larmor motion has been converted to ion kinetic energy. This suggests that the calculated beam divergence caused by separation may be somewhat independent of the mechanism by which the plasma is initially created and accelerated. As such, these calculations may shed light on the field separation issues associated with other plasma propulsion concepts that make use of magnetic nozzles.[5,6,7]

Because it may be impractical to design high-current magnet coils with radii much larger than the plasma engine radii, it is desirable to find a way to reduce beam divergence without excessively increasing the radii of primary coil used to produce the field in the magnetic nozzle. We suggest the use of the "plasma lens" as a potential approach to solving this problem. The concept of the plasma lens is similar to that of the magnetic lenses used to focus charged particles in high energy physics, with the difference that the plasma lens works with a quasi-neutral beam of plasma and must therefore be designed to account for collective effects.

We have analyzed the theoretical feasibility of using the plasma lens to reduce the divergence of the plasma beam produced by an ECR plasma engine. To do this, we have conducted calculations similar to those used to produce Fig. 1 and Fig. 2 but we assumed that four low-current large-radius current loops were added to the simple single-turn magnet assumed in the calculations of Fig. 1. The radius of these additional current loops was assumed to be 0.6 m. The current level in the loops was taken to be 200 A each. The direction of the current was taken to be opposite to the direction of the current in the primary coil. This was done to produce a more abrupt magnetic field divergence downstream of the primary coil to force a more abrupt separation of the plasma from the field. The axial locations of the four loops, which were arranged on center-line, were .4, .525, .65, and .775 meters down stream.

Fig. 3 shows the calculated effects of adding this magnetic lens to the magnetic nozzle. In Fig. 3 the dotted lines are the first seven plasma trajectories from Fig. 1. The solid lines in Fig. 3 are the plasma trajectories with the added magnet coils. Because the field of the plasma lens coil is aligned opposite to the field of the primary magnet, the plasma diverges more rapidly at first with the lens than without it. However, in the process of completely separating from the magnetic nozzle, the calculated plasma stream lines actually bend back toward center-line and divergence is less with the lens than without it. The four black squares displayed in Fig. 3 show the radii and axial locations of the lens coils.

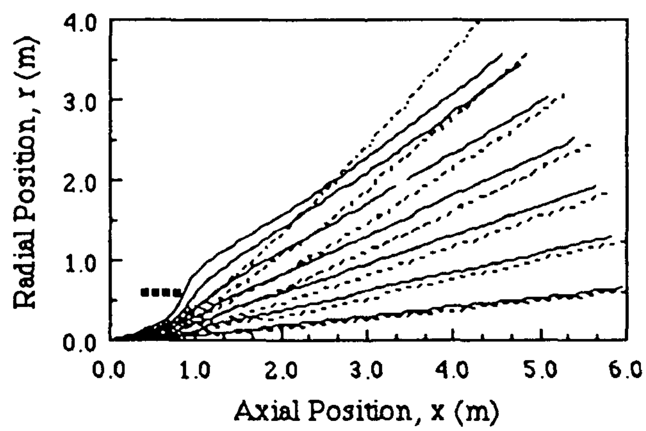

Fig. 3 Calculated plasma trajectories with and without a plasma lens added to the magnetic nozzle. Solid lines are trajectories with the plasma lens, dotted lines are without.

This theoretical study provides a simple technique for predicting the shape of the plasma plume of an ECR plasma accelerator. Using this technique, we conclude that the ECR plasma accelerator can be used to produce an accelerated plasma beam which detaches from the field of the magnetic nozzle without collision-induced diffusion and without ohmic heating of the plasma. Further, the magnitude of the beam divergence can be controlled by controlling the shape of the field of the magnetic nozzle. The concept of a plasma lens was introduced as a means of controlling beam divergence. Calculations suggest that the plasma lens can reduce beam divergence without increasing the diameter of the primary coil used in the magnetic nozzle.

2. Quasi-One-Dimensional Steady-State Model of Nonequilibrium Processes

Nonequilibrium and radiation effects are treated using a steady-state, quasi-one-dimensional, three-component model. The three components included are the electron fluid, the ion fluid, and the neutral gas, which is addressed under the assumption of rarified flow. Using this model we can solve for plasma density, gas atom density, axial velocity, and each of two components of the electron temperature (perpendicular and parallel to magnetic field lines). Source terms are present in the model to account for phenomena such as coupling microwave power into the plasma at ECR, collisional energy transfer between the perpendicular and parallel components of the electron temperature, cross-field (Bohm) diffusion, ionization, radiation, and ambipolar diffusion.

This model represents the first successful attempt to simultaneously analyze all of the many phenomena which are present in ECR plasma acceleration. Past work in this field has been successful in treating only one or two of these phenomena or have treated several of these phenomena separately without fully accounting for the non-linear interactions which we have been found to be present. For this reason we refer to our model as the first unified theory of ECR plasma acceleration.

The basic set of equations which embody the model have been derived in previous publications.[4] We used the LSODE computer program for solving systems of ordinary differential equations to calculate numerical solutions to the equations. Figs. 4, 5, and 6 present the results of one such calculation. The boundary conditions used in these calculations include an initial gas velocity equal to the initial plasma velocity of 100 m/s, an initial electron temperature of 2.5 eV, an initial neutral gas density of 6×10^{18} m^{-3}, and an inlet ionization fraction of 0.1. Coupled ECR power in this case was taken to be 20 kW/m^2 The ECR heating region was assumed to be centered at z=0.1 m falling off up-stream and down-stream as a Gaussian function over a characteristic length of 1 cm.

Fig. 4 shows the variation of plasma velocity as a function of z, the distance down-stream from the window Fig. 5 shows the variation of neutral atom and plasma density with z. Fig. 6 shows the variation of the perpendicular and parallel components of the mean electron thermal energy with z. This calculation predicts losses due to ionization, radiation, diffusion, propellant utilization, and particle collision phenomena which total approximately 25 percent of coupled microwave power. These predicted losses of only 25 percent for an un-optimized thruster design are very encouraging.

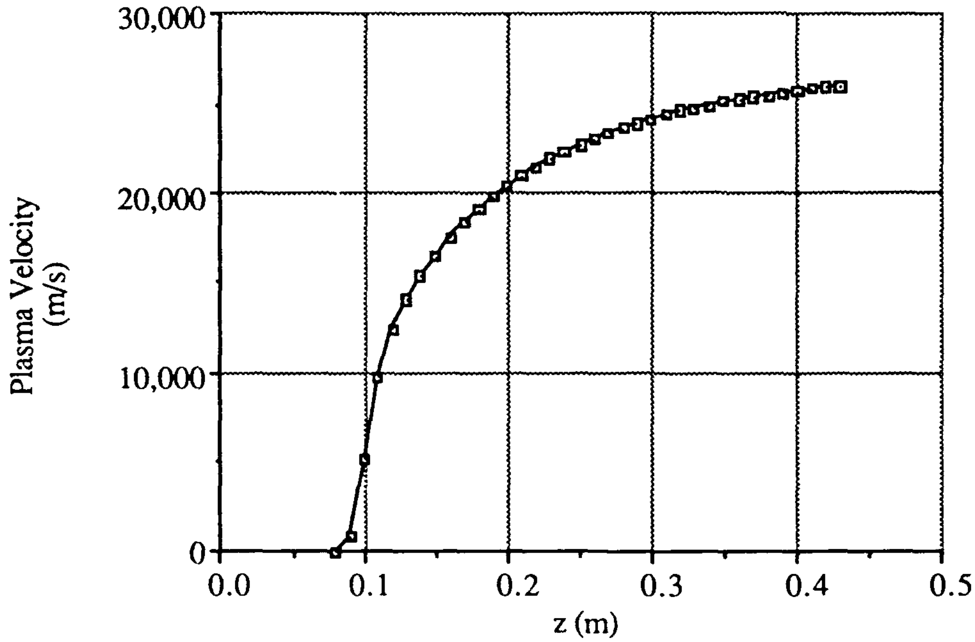

Fig. 4 Plasma velocity as a function of distance from dielectric window calculated from quasi-one-dimensional model.

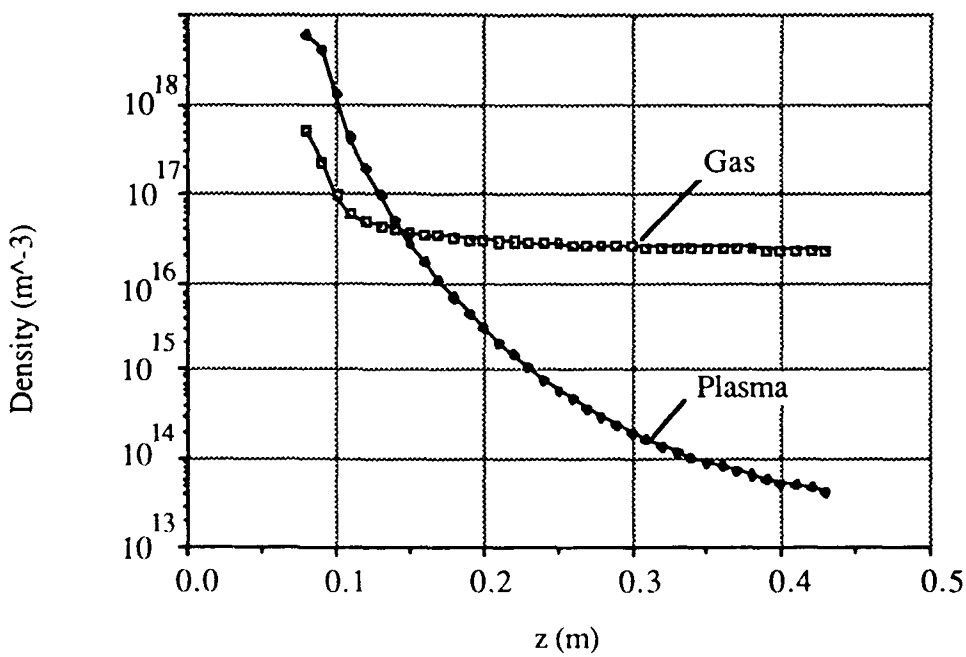

Fig. 5 Plasma density as a function of distance from dielectric window calculated from quasi-one-dimensional model.

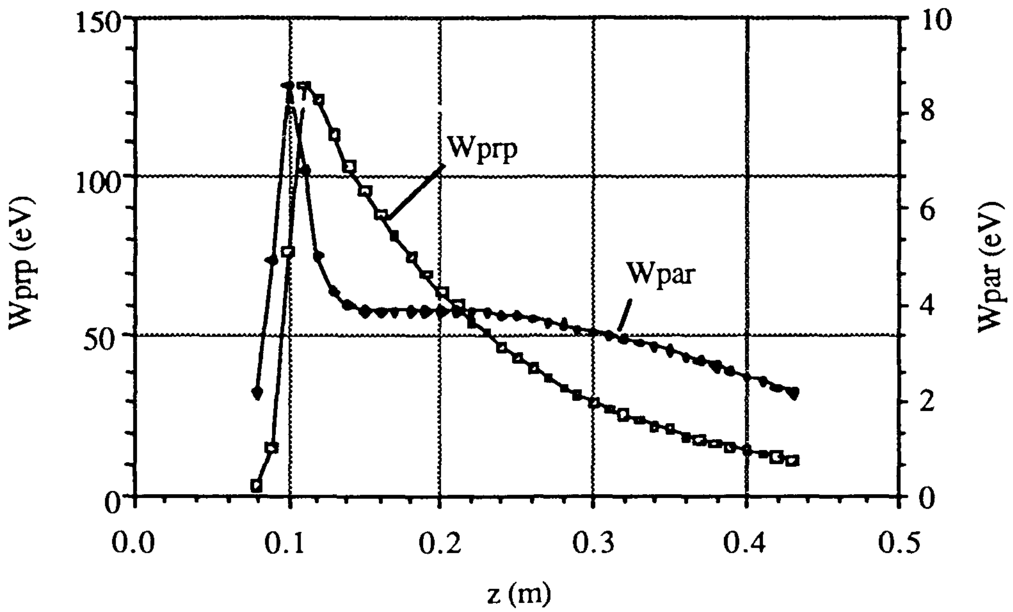

Fig. 6 Mean electron energy as a function of distance from dielectric window calculated from quasi-one-dimensional model.

For the present research effort, it was necessary to incorporate the effects of axial heat transport and vacuum system back pressure into the existing model. Once verified by comparison with our experimental measurements, the present theory can then be used to predict the theoretical performance of the ECR plasma engine. To this end, the nonequilibrium and radiation effects model has been modified to include modified Spitzer-Harm heat conduction terms for axial heat transport along magnetic field lines. We are presently performing numerical calculations based on this modified model for comparison with our experimental measurements.

B. Experimental Work

An experimental test bed has been developed as part of this activity and has been described in references 3 and 4. Several diagnostic tools have been used to measure physical parameters of interest in further developing a basic scientific understanding of this device. Our diagnostics include a gridded energy analyzer, a Faraday cup current density analyzer, Langmuir probes, emissive probes, and a diamagnetic loop. We have measured the accelerated ion energy distribution, the accelerated plasma density (and hence the propellant utilization), perpendicular and parallel components of the electron temperature, the magnitude and spatial variation of the plasma potential, and plasma beta in the ECR heating region.

Our measurements have shown that the propellant utilization, ion energy, plasma potential, and plasma beta are consistent with theoretical predictions. However, electron temperatures have been lower than predicted by theory. The most likely explanation for this observation is that axial conduction of electron thermal energy is carrying a significant fraction of the coupled power down-stream where it is dissipated via inelastic collisions of electrons with neutral atoms in the vacuum tank. A summary of some of our early experimental results has been published in reference 4. A more complete and detailed presentation of our experimental results will be included in Mr. Sercel's PhD thesis.

C. Closing Thoughts

The first years of this research effort culminated in the development of a unique research apparatus which has allowed the first comprehensive experimental study of the ECR plasma engine. A review of similar efforts to develop apparatus and theoretical models for the study of other advanced propulsion concepts suggests that these first steps are both costly and difficult. However, considering the benefit afforded by the interaction between our experimental and theoretical studies, we are convinced that this cost is more than justified. Because the experimental data taken thus-far generally agrees with the trends predicted by our theoretical work, we are especially encouraged about the future of this research effort.

The goal of our future effort, which will include significant NASA funding, must be to experimentally and analytically advance the state of understanding of the ECR plasma accelerator. Only in this way can the full potential of the ECR device be realized in terms of high specific impulse, high thrust efficiency, long life, high power, and the flexibility to use convenient propellants. Further, the rapid rate of progress to date in this research suggests that the total cost of developing ECR propulsion technology may be far less than that which has been spent on other electric propulsion devices.

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III PERSONNEL

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IV. PUBLICATIONS

1. J. C. Sercel, "A Simple Model of Plasma Acceleration," AIAA paper 90-2597, presented at the 21st International Electric Propulsion Conference, Orlando, FL, July 1990.

2. J. C. Sercel, PhD Thesis, "An Experimental and Theoretical Study of the ECR Plasma Engine Concept," California Institute of Technology, Expected Fall 1990.

V. INTERACTION WITH OTHER INDUSTRIAL AND GOVERNMENT RESEARCH GROUPS

Mr. Sercel maintains close contact with the Electric Propulsion Technology and the Microwave Transmitter groups at JPL. The Electric Propulsion Technology and the Microwave Transmitter groups at JPL have provided considerable material and technical support free-of-charge for the ECR basic research program. Mr. Sercel also maintains contact with a group of researchers at JPL conducting ongoing systems studies of the application of ECR propulsion technology to missions of planetary exploration. In addition, Mr. Sercel continues exchange of information with various groups at the Lawrence Livermoore National Laboratory, Pennsylvania State University, and the Massachusetts Institute of Technology.

VI. FUTURE FUNDING NEEDS

Based on the encouraging theoretical and experimental results obtained thus-far in this effort we believe this research should be continued. Further, by effectively coordinating this work with the larger NASA funded experimental effort at JPL the cost of this program will be kept relatively modest.