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Electron-Cyclotron-Resonance (ECR) Plasma Acceleration

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ELECTRON-CYCLOTRON-RESONANCE (ECR) PLASMA ACCELERATION

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Abstract

A research effort directed at analytically and experimentally investigating Electron-Cyclotron-Resonance (ECR) plasma acceleration is outlined. Relevant past research is reviewed. The prospects for application of ECR plasma acceleration to spacecraft propulsion are described. It is shown that previously unexplained losses in converting microwave power to directed kinetic power via ECR plasma acceleration can be understood in terms of diffusion of energized plasma to the physical walls of the accelerator. It is argued that line radiation losses from electron-ion and electron-atom inelastic collisions should be less than estimated in past research. Based on this new understanding, the expectation now exists that efficient ECR plasma accelerators can be designed for application to high specific impulse spacecraft propulsion.

Acronyms and Abbreviations

D-He^3	Deuterium Helium-Three
ECR	Electron-Cyclotron-Resonance
GE	General Electric
JPL	Jet Propulsion Laboratory
LeRC	Lewis Research Center
NASA	National Aeronautics and Space Administration
TE	Transverse-Electric

Nomenclature

B	magnetic induction vector, T
E	energy, J or eV
e	electron charge (1.602×10^{-19} coul)
F	force, N
K	Boltzmann's constant
L	length of accelerator, m
m	mass of electron (9.1×10^{-31} kg)
M	mass of ion, kg
n	number density, m^{-3}
p	power per unit volume, W/m^3
R	position vector, m
v	velocity, m/s
U	energy, J or eV
V	electrostatic potential, volts
T	temperature, Kelvin or eV

Greek

μ	magnetic dipole moment
σ	reaction cross section, m^2
τ	time constant, s

Subscripts

A	acceleration
B	Bohm
e	electron
ex	excitation
i	ionization
j	summation variable
l	refers to lowest energy level
p	perpendicular
r	relative
sp	space charge induced
tot	total

I. Introduction

ECR plasma acceleration is an electrodeless process which promises to efficiently use microwave frequency electromagnetic radiation to accelerate a tenuous plasma to velocities of use for high specific impulse spacecraft propulsion. The advantages of high specific impulse propulsion are well known in the aerospace community. If high specific impulse propulsion technology can be implemented, propellant mass savings and associated cost savings can be obtained for many current missions, and a wide variety of desirable new missions can be enabled. Electric propulsion represents the most likely near-term possibility for achieving high specific impulse propulsion. More advanced systems such as beamed energy propulsion or fusion propulsion still remain futuristic concepts. This paper re-examines ECR plasma acceleration for application to electric propulsion, beamed energy propulsion, or fusion propulsion.

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Figure 1 shows a conceptual schematic of an ECR plasma accelerator. Transverse-Electric (TE) mode microwave radiation is introduced through a dielectric window into a neutral gas region via a waveguide. The neutral gas region can be in an extension of the waveguide, in a resonant cavity, or in a flared portion of the waveguide that has a different internal radius than the power transmission waveguide. A solenoid coil co-axial with the waveguide, but larger in radius, surrounds the neutral gas region. This coil is designed to produce a magnetic field which decreases in intensity away from the dielectric window in the direction the microwave radiation propagates.

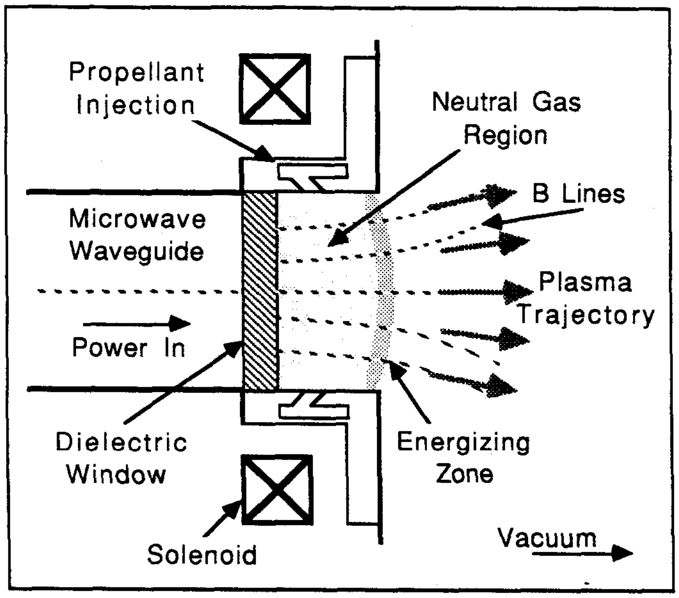

Fig. 1 Schematic of ECR Plasma Accelerator.

A propellant, such as argon, is introduced into the neutral gas region via peripherally located injection ports. The intensity of the solenoid magnetic field in the energizing zone is adjusted so that the electron-cyclotron frequency is equal to the frequency of the applied microwave radiation. This frequency matching provides a resonance between the microwave field and the electron-cyclotron motion that enhances microwave-to-plasma coupling. Some ionization occurs in the neutral gas region, but coupling there is limited because the electron-cyclotron motion is not at resonance with the microwave radiation. The gas enters the energizing zone via free molecular diffusion. In the energizing zone the gas atoms are ionized by the microwave radiation through electron-atom collisions in a cascading process. The microwave energy is coupled to the electron-cyclotron motion in the energizing zone, which results in electron energies of 200 to 1000 eV.

These free electrons move in Larmor orbits producing a field of magnetic dipoles with axes aligned opposite to the axis of the solenoid magnetic field. The opposition between the electron-Larmor-orbit dipole field and the applied diverging solenoid field results in a net force on the electrons. As this force accelerates the electrons, a space-charge potential is induced which accelerates the ions with the electrons down-stream toward a vacuum region. The quasi-neutral plasma then separates from the magnetic field with minimal loss and moves away from the device into the vacuum region.

Overall conversion of microwave power to jet power involves several possible loss mechanisms including: (1) reflection of the applied microwave power, (2) exhaust plume divergence, (3) nonuniformities in the exhaust velocity profile, (4) propellant ionization energy costs, (5) ion-electron recombinations, (6) incomplete propellant ionization, (7) plasma interactions with the walls of the accelerator, and (8) radiation from the plasma.

II. History and Related Research

ECR plasma acceleration was first investigated both experimentally and analytically for application to electric propulsion in the 1960s. Three groups of researchers were involved in this early work: (1) a group at General Electric Corporation[1] funded by Lewis Research Center (LeRC), (2) a NASA group at LeRC,[2] and (3) a group at the University of Tokyo.[3] Although the early research was conducted with somewhat primitive apparatus and theoretical models (by today's standards), enough research was done to verify the basic concept of the process. At the time of the investigation, however, microwave sources were quite massive and inefficient. Meanwhile, significant progress was being made on dc electric propulsion devices which showed promise of acceptable performance using the technology and analysis tools of the 1960s. By the middle of that decade, these advances had presaged the temporary end of research into the physics of ECR plasma acceleration.

A review of the early research publications and communication with the investigators suggests that state-of-the-art microwave technology and plasma diagnostic tools can be used to make ECR plasma acceleration an important part of modern spacecraft propulsion technology.

The majority of the early experimental work on this type of plasma accelerator was conducted at the Space Sciences Laboratory of the General Electric Company (GE) and funded by the Lewis Research Center (LeRC).[1,4] In this experimental effort, several different ECR plasma thrusters were tested. Various arrangements of gas injection schemes, waveguide designs, and window materials were evaluated. Thrust was measured for a variety of configurations at power levels of up to a few kilowatts using several propellants. Over 95 percent of the incident microwave power was observed to be deposited in the plasma stream.[4] A maximum efficiency for conversion of microwave power to jet power of 0.4 was reported at specific impulses of a few thousand seconds.[1] However, the validity of many of the early thrust measurements was questioned. It was suggested that entrainment of gas from the vacuum chamber into the energizing zone was increasing the effective mass flow rate and producing erroneously high thrust measurements.[4] In measurements not subject to concern about gas entrainment, thrust efficiency was only about 10 percent, and specific impulse was measured to be less than 2000 seconds. Electron energy measurements in the plasma energizing zone suggested that electron thermal motion was effectively converted to jet power.[4] An unknown mechanism was robbing the electrons of their thermal energy prior to the plasma acceleration, thereby preventing optimal accelerator performance.

It was suggested at the time that this loss mechanism was line radiation caused by electron-atom inelastic collisions.[4] Synchrotron and Bremsstrulung radiation losses are several orders smaller than line radiation losses. However, recent analysis suggests that line radiation also could not have been responsible for the magnitude of the observed energy loss. It now appears that plasma was diffusing to the walls of the accelerator across magnetic field lines. This diffusion was probably responsible for the measured low thrust efficiencies and can be limited through informed accelerator design.

The first publication of a theoretical analysis of ECR plasma acceleration occurred several years after the initiation of experimental work at General Electric Corporation (GE). In this theoretical treatment, which was accomplished by Kosmahl at Lewis Research Center (LeRC), conservation of the electron-cyclotron dipole moment, zero collisions, and axisymmetrical steady-state fields were assumed.[2] A significant conclusion of this analysis was that the plasma trajectory does cross the magnetic field lines, even without particle collisions, and that the plasma can emerge as a well-defined beam.

This conclusion was in contrast to the earlier theoretical analysis of Kilpatrick.[5] Kilpatrick's work indicated that a plasma beam ejected from a diverging magnetic field will closely follow field lines; unless the plasma is initially well-collimated with high initial directed kinetic energy.[5] The critical difference between Kilpatrick's analysis and that of Kosmahl was that Kosmahl studied a non-equilibrium plasma in which most of the thermal energy was stored in electron motion. Kilpatrick studied a plasma in which collisions resulted in near thermal equilibrium of all charged species. Furthermore, Kilpatrick's analysis did not fully account for the magnetic dipole-moment force that is responsible for ECR plasma acceleration.

Kosmahl defined a propulsive efficiency to account for momentum losses resulting from radial acceleration of the plasma during separation from the magnetic field. This propulsive efficiency depends primarily on the solenoid geometry and the position at which plasma of a given radial extension is introduced to the field. Kosmahl showed that propulsive efficiencies between 0.90 and 0.97 could be expected for a variety of thruster configurations. Kosmahl's dipole moment calculation is discused later in this paper in Section IV.

A review of the experimental work published by Nagatomo at the University of Tokyo on ECR plasma acceleration indicates that the work performed by the Japanese on this device was directed at experimentally obtaining a fundamental understanding of the nature of the acceleration mechanism.[3] Nagatomo developed several useful measuring techniques which gave accurate information on the basic physics of this process. Specifically, Nagatomo used: (1) unusually small and sensitive electromagnetic probes to measure microwave field strength within the accelerator without disturbing the plasma, (2) hot Langmuir probes to measure the electrostatic potential of the accelerating plasma, and (3) an innovative, simple thrust balance to provide a direct measurement of the propulsive force between the plasma and the solenoid coil. The thrust measuring device developed at the University of Tokyo is especially interesting, because it obviates having to place both the thrust balance and waveguide structure in a vacuum chamber.

Current work on the absorption of microwave radiation into a plasma by ECR is the subject of intensive investigation by groups studying magnetic confinement fusion.[6] A few key differences exist, however, between the fusion application of ECR absorption of microwave radiation and the propulsion application of this mechanism. First, the fusion community is interested in the higher temperatures appropriate to nuclear fusion research. Second, in the fusion application it is desirable to transfer the electron thermal energy to the ions. In the propulsion application it is desirable to transfer the electron kinetic energy only to the directed kinetic energy of the flowing plasma. Finally, the high magnetic fields associated with magnetic confinement fusion research mandate radiation frequencies one to two orders-of-magnitude higher than those required for the propulsion application. In summary, it is much more difficult to apply ECR heating to fusion research than to plasma acceleration for spacecraft propulsion. It is worth noting that the interest in high-power, high-frequency microwave sources for fusion research has been an important factor in the recent development of high-power microwave sources.

At least two research efforts in microwave thermal propulsion are complementary with the present research on ECR plasma acceleration. Asmussen[7,8] and Micci[9,10] have both been studying thermal propulsion applications of microwave technology. The microwave apparatus developed by these researchers is similar to that which will be used in the experimental portion of the research discussed here.

III. Present Research Program

The goal of the recently initiated present research program is to develop a unified understanding of ECR plasma acceleration. To accomplish this goal a combined analytical and experimental program is being conducted.

As part of the analytical part of this program a literature survey was completed, the results of which are described in Section II of this paper. This literature survey provided background for the preliminary scoping calculations presented in Section IV of this paper. To summarize, the collisionless dipole moment calculation of Kosmahl has been verified through numerical solution of the equations of motion for electrons and ions in ECR plasma acceleration. Also, the effects of elastic and inelastic collisions have been evaluated to first approximation. Finally, it has been shown that cross-field diffusion can result in significant wall losses if not correctly accounted for in accelerator design.

The next activity planned in this program is to gain a more complete understanding of ECR plasma acceleration based on a unified analysis of the phenomena that act in concert to produce ECR plasma acceleration. To accomplish this end, a numerical model of ECR acceleration is being developed. It is expected that this numerical model will further illuminate the physics of ECR plasma acceleration, and will provide valuable information to be used in the detailed design of an experimental program.

In the experimental program, a research device will be constructed and tested. Performance of this device will then be compared to the predictions of the numerical model to point out deficiencies of understanding. Interferometric measurements of the Doppler shift of optical emission from the exhaust plume will be used to determine the exhaust velocity profile. Langmuir probes will be used to measure the temperature and density of electrons in the plasma. Electromagnetic probes will be used to measure the local intensity of the microwave field in the energizing zone to characterize the coupling of microwave power to the plasma.

Table 1 presents estimated design characteristics and operating parameters of the planned ECR research device. The values given are approximate and are presented only to communicate the nature of the experimental program and the physical regime in which the device will operate.

Although the focus of the current program is on the physics of ECR plasma acceleration, this program is also expected to identify practical constraints associated with the eventual feasibility of applying this process to spacecraft propulsion. Among the practical constraints of interest are the limits to the useful range of exhaust velocity and power level that can be met by ECR propulsion. This research will also provide valuable information for use in selecting of the best propellant fluid from the wide range of fluids which now appear to be applicable.

IV. Preliminary Theory of ECR Plasma Acceleration

Fundamental to ECR plasma acceleration is the conversion of electron Larmor motion into

Table 1. Estimated Design Characteristics and Operating Parameters of Planned ECR Research Device.

Catagory	Parameter	Value
Device Characteristics	R-F Power Level	1 kW
	Microwave Frequency	2.45 GHz
	Accelerator Area	0.05 m^2
	Peak Magnetic Field On Axis	0.1 Tesla
	Solenoid Diameter	0.3 m
	R-F to Jet Efficiency	≈ 0.5
	Vacuum Required	10^{-5} torr
Propulsion Parameters	Working Fluid	Argon
	Exhaust Velocity	30,000 m/s
	Thrust	10^{-2} N
	Mass Flow Rate	10^{-6} kg/s
	Atom Flow Rate	10^{19} s^{-1}
Plasma Parameters	Electron Temperature	10^2 eV
	Ion Temperature	10^{-1} eV
	Electron Larmor Radius	10^{-4} m
	Ion Larmor Radius	10^{-3} m
	Peak Atom Density	10^{18} m-3
	Peak Electron or Ion Density	10^{17} m-3
	Debye Length	10^{-4} m

directed kinetic energy of flowing plasma via expansion through a diverging magnetic field. However, to appreciate the limitations of ECR plasma acceleration, several additional phenomena must be understood as they relate to this process. These phenomena include: (1) electron-electron elastic scattering, (2) coupling of microwave power to plasma at electron-cyclotron-resonance, (3) line radiation and inelastic collisions, and (4) diffusion of plasma across magnetic field lines. These processes are briefly discussed below.

A unified theory of ECR plasma acceleration is not yet complete, so the following discussion presents only preliminary findings. The calculations shown are based on many simplifying assumptions which are being removed in current work. The purpose of this discussion is to communicate an understanding of the operation of this device and to suggest an achievable performance level.

Plasma Acceleration Mechanism

As mentioned earlier in this paper, a collisionless model of ECR plasma acceleration was developed by Kosmahl.[2] In Kosmahl's model, a tenuous, collisionless plasma was assumed in the solution of a three-dimensional equation in which ion stream-wise motion is tied to electron stream-wise motion via induced space charge fields. Initially, the plasma enthalpy in this model is stored as magnetic dipole energy associated with electron Larmor motion $[\mu B=(1/2)mv_p^2]$. Following the method established by Alfven, the complete motion of the electrons was described as the superposition of the Larmor motion about B-lines, and the translational motion of the electron guiding centers.

The governing equations used in Kosmahl's analysis are presented next. The force on a dipole in a diverging magnetic field is given by:

$$\mathbf{F}_\mu = \nabla(\boldsymbol{\mu}\cdot\mathbf{B}) \quad (1)$$

In a plasma such as applicable in this process, the mean dipole vector of gyrating electrons is anti-parallel to the local B-field. Eq. (1) reduces to:

$$\mathbf{F}_\mu = -\mu\,\nabla B \quad (2)$$

The total force on a gyrating electron is:

$$\mathbf{F}_{tot} = \mathbf{F}_\mu - e(\dot{\mathbf{R}}_e \times \mathbf{B} + \nabla V_{sp}) = m\ddot{\mathbf{R}}_i \quad (3)$$

and the total force on an ion in this model is:

$$\mathbf{F}_i = e(\dot{\mathbf{R}}_i \times \mathbf{B} + \nabla V_{sp}) = M\ddot{\mathbf{R}}_i \qquad (4)$$

where V_{sp} is the space-charge-induced potential, $\mathbf{R}$ is the position vector of the guiding center trajectories, and m and M are the electron and ion mass, respectively. Kosmahl solved these equations numerically together with the continuity equations. The most important results of his computation can be summarized in a few sentences. In the absence of collisions, the plasma trajectory does not depend on the ion mass or the magnitude of the dipole moment, but is strongly affected by the geometry of the magnetic field. Both ∇V_{sp} and V_{sp} are approximately proportional to the product μB, which goes to zero as the plasma moves away from the accelerator. The final azimuthal energy of the plasma particles was found to be negligibly small compared to the translational energy associated with their guiding center trajectories.

Elastic Scattering of Electrons

Elastic scattering of electrons has two important effects on the process of ECR plasma acceleration. The first of these effects is dynamical friction on the electron motion. This tends to thermalize the electrons and somewhat reduce the total energy available for plasma acceleration. Second, the scattering of electrons upstream from the energizing zone into the neutral gas region results in the production of ions in that region. This upstream flow of plasma could also lead to wall losses or sputtering from the dielectric window if not properly accounted for in accelerator design.

For the plasma conditions of Table 1, the characteristic time for electron-atom elastic scattering collisions is estimated to be of order 10^{-6} s in the energizing zone of an ECR plasma accelerator. This estimate is based on an assumed elastic scattering cross section of 5×10^{-20} m^2. The characteristic time for electron-electron scattering collisions is two orders larger than for electron-atom scattering. The mean electron velocity in the stream-wise direction in the energizing zone is the same as the mean ion stream-wise velocity there and is expected to be of order 10^3 m/s (based on numerical solution of Kosmahl's dipole-moment problem).

At the down stream point where the electron thermal energy is reduced to half of its original value, the mean stream-wise velocity of both electrons and ions will be on the order of 10^4 m/s. From conservation of mass in steady-state operation, this implies that the ion density must fall to approximately 10^{16} m^{-3} at this halfway point. The mean time between electron-ion elastic scattering collisions at this point is of order 10^{-4} s. From this information, the mean stream-wise distance between electron elastic scattering collisions in the energizing zone, and at a point halfway through the acceleration process, is 10^{-3} m and 1 m, respectively.

Because electrons in the energizing zone move an average of only 10^{-3} m before undergoing scattering collisions, their kinetic energy is distributed between the three translational degrees of freedom. Therefore, although the scattering frequency is much lower than the electron-cyclotron frequency, only two thirds of the electron's kinetic energy contribute to the electron magnetic dipole moment, and only about two thirds of the electron motion is initially available to supply dipole moment effects for plasma acceleration. As the plasma begins to accelerate and the kinetic energy associated with the electron transverse motion is converted to directed motion of the plasma, some of the energy in longitudinal electron motion is returned to transverse motion through further elastic scattering. This continues until the plasma becomes essentially collisionless, approximately halfway through the acceleration process.

At the point where collisions become negligible, any electron kinetic energy remaining in longitudinal modes of motion is essentially frozen out of the flow and does not contribute to further dipole moment plasma acceleration. Some of the electron energy remaining in longitudinal modes of motion may contribute to propulsive thrust and enhance efficiency by producing ambipolar diffusion in the direction of the plasma flow; but such a process has not yet been carefully studied.

This approximate analysis suggests that elastic scattering of electrons may reduce the effective efficiency of the acceleration process from the collisionless value of over 90 percent to as low as, perhaps, 60 percent. It is likely that ambipolar diffusion and the return of electron kinetic energy to transverse motion through scattering could raise this value to as high as 85 percent, but further analysis will be required to verify this assertion.

As mentioned above, elastic scattering of electrons has the additional effect of directing some electrons upstream from the energizing zone into the neutral gas region. These electrons will not travel upstream at their thermal diffusion velocity, but will move by ambipolar diffusion. In other words, a local electric field is established with a polarity that retards the upstream migration of electrons while, at the same time, it accelerates the migration of ions. The mean migration velocity of the two charged species can be simply shown to be equal to the ion acoustic velocity. Based on the plasma parameters of Table 1, the ion acoustic velocity is estimated to be of order 10^4 m/s.

Moving at the ion acoustic velocity with a characteristic time for elastic scattering of 10^{-6} s, the scattered electrons travel a mean distance of 10^{-2} m before undergoing further scattering collisions with atoms in the neutral gas region. Approximately the same mean distance is required before these electrons undergo inelastic collisions with the atoms in the neutral gas region, because the total electron-atom inelastic scattering cross section is similar to the elastic cross section. The primary effect of these inelastic collisions is damping of the motion of the electrons via ionization and excitation of the neutral gas atoms. Recombination reactions are much less likely. This mechanism can ionize atoms as far as several centimeters upstream of the energizing zone. Also, if the neutral gas region is too narrow, plasma can impact the dielectric window, resulting in sputtering and energy loss.

Microwave-to-Plasma Coupling

For the acceleration mechanism described above to be of use, not only must the atoms be ionized, but the electrons must be energized. This is accomplished by coupling microwave radiation to electron motion within the energizing zone. In this application, the microwave radiation propagates in a direction parallel to the magnetic field lines.

This coupling problem is classically addressed by treating the plasma as a continuum medium with an index of refraction having both real and imaginary parts. The results of this classical treatment of the propagation problem are well known and is outlined in a few sentences: The propagating radiation displays one cutoff and one resonance, with the resonance occuring at the lower of the two frequencies and being equal to the electron-cyclotron orbital frequency. Below resonance, propagation occurs in what is commonly referred to as the whistler mode, with some attenuation of the microwave power resulting from electron collisions within the plasma. At resonance, ideal theory suggests that no propagation will occur; all the electromagnetic radiation is either absorbed or reflected by the plasma.

In ECR plasma acceleration, damping due to Doppler broadening associated with electron motion (an effect quite similar to the phenomenon of Landau damping) has a favorable impact on the reflection and attenuation characteristics of the plasma.[11] Specifically, the resonance effect actually occurs over a frequency band with a width corresponding to an appreciable fraction of the field frequency. Furthermore, because the plasma in ECR acceleration is flowing, the effects of particles being carried downstream from their point of origin must be considered. The longitudinal acceleration of charged species, as they are created, results in a gradual plasma boundary which reduces reflection of the microwave radiation.

These effects have been experimentally observed to reduce reflection to negligible levels (resulting in over 95 percent of the applied microwave power being absorbed into the plasma) at electron densities appropriate to ECR acceleration.[4] The thickness of the energizing zone was observed in past research to be fixed at a few centimeters as determined by electron damping effects.[1,3,4] This observation has important implications for the design of useful ECR devices. Specifically, it allows the ion production rate in an ECR accelerator to be controlled simply by regulating the conditions in the neutral gas region. This is true because the rate at which atoms diffuse out of the neutral gas region into the energizing zone is a function of the conditions in the neutral gas region.

For a specified mass flow rate, the mean density of gas atoms entering the energizing zone varies inversely with the mean thermal diffusion velocity. Because the mean thermal diffusion velocity is proportional to the square root of the gas temperature, controlling gas temperature effectively controls gas density. Increasing gas density increases the rate of production of ions in the energizing zone because it increases the electron-atom collision frequency.

To see how the ionization rate can be controlled, consider that if the atom temperature in the neutral gas region is 600 Kelvin, the mean thermal diffusion velocity is about 180 m/s. To meet the mass flow rate and other conditions of Table 1, the resulting gas density is approximately 10^{18} m^{-3}, and the required thickness of the energizing region is 10^{-2} m, as observed. If the atom temperature were increased to 1500 Kelvin, the mean thermal diffusion velocity would increase to approximately 550 m/s. If this mass flow rate were maintained, the resulting atom density would be approximately one third its prior value. The required thickness of the energizing zone, therefore, would triple. If the required thickness of the energizing zone became too large to be maintained by electron damping effects, atoms would pass through the energizing zone without being ionized. The loss of such escaping neutral atoms would reduce the propulsive efficiency of this device.

Double ions can be produced in this device through either electron-atom or electron-ion collisions. For the plasma species considered for use in this device, double ionization cross sections for electron-atom reactions at energy levels of interest are one order smaller than single ionization cross sections.[12] The product of the density of ions and electrons in the energizing zone of the accelerator is less than one tenth the product of the density of atoms and electrons. The cross section for electron-ion double ion production is similar to the cross section for electron-atom ionization at relevant energy levels. Therefore, electron-ion, double ion producing collisions are expected to take place at or below the rate at which electron-atom double ion producing reactions occur. Hence, double ions are expected to account for ten to twenty percent of the ions produced in ECR plasma acceleration. Future analysis will be directed at obtaining a more complete understanding of the effects of these double ions.

Other Inelastic Collision Losses

A preliminary analysis of the losses due to other inelastic collision processes, such as electron-atom collision-excited line radiation will now be presented. Neglecting double ionizations, for an approximate calculation, and assuming the accelerated plasma is fully ionized, the power lost per unit volume of plasma due to ionization and excitation reactions can be written as:

$$p = n_e n_a \left(<\sigma_i v_r> U_i + \sum_j <\sigma_j v_r> U_j \right) \qquad (5)$$

where U_i is the ionization energy, σ_i is the ionization cross section, v_r is the electron speed relative to atoms, and the summation over j refers to the jth excitation reaction resulting from electron-atom collisions in which U_j refers to energy level and σ_j refers to the collision cross section to produce that excited state. The notation: $<\sigma v_r>$ represents the product of a reaction cross section and the electron velocity averaged over the electron velocity distribution. Assuming no recombination or wall losses, Eq. (5) can be normalized to produce an expression for the energy expended in producing each ion:

$$E_i = U_i + \sum_j (<\sigma_j v_r> U_j)/<\sigma_i v_r> \qquad (6)$$

The term under the summation sign in Eq. (6) may be approximated by considering a single equivalent lumped excited state characterized by a total excitation collision cross section, σ_{ex}, and a lumped excitation energy U_{ex}. For tenuous plasmas, U_{ex} may be approximated by:

$$U_{ex} = (U_l + U_i)/2 \qquad (7)$$

where U_l is the lowest excitation energy level.[13] Using this lumped excitation approximation, Eq. (6) becomes:

$$E_i = U_i + <\sigma_{ex} v_r> U_{ex}/<\sigma_i v_r> \qquad (8)$$

For argon, U_l and U_i are both approximately 15 eV. Because the ratio of the two averaged products in Eq. (8) is close to unity for argon at the energy level of interest, one would expect that the energy cost of producing ions through inelastic collision processes in this device would be approximately 30 eV. If such an "ion production cost" could be achieved in ECR plasma acceleration, very efficient accelerator operation would be expected. Such high efficiency was never repeatably observed in the experimental work of the 1960s. Therefore, inelastic collision processes alone can not account for the low thrust efficiencies measured.

Cross-Field Diffusion

The additional loss mechanism that must be considered to accurately describe the performance of ECR plasma acceleration as applied to spacecraft propulsion is the power lost to the walls of the accelerator due to diffusion of charged, energized species across magnetic field lines. To understand this loss mechanism, the characteristic time required for diffusion to the walls was compared to the time required for plasma acceleration through the accelerator due to the dipole moment body force. The ratio of these two quantities was then used to characterize the relative significance of cross-field diffusion in ECR plasma acceleration.

The time constant for diffusion across magnetic field lines in a cylindrical geometry such as the ECR plasma accelerator can be estimated by the Bohm time:

$$\tau_B \approx 8eBR^2/KT_e \qquad (9)$$

where B is the magnetic field strength, R is the radius of the accelerator, and T_e is the electron temperature.[14, 15] Eq. (9) can be derived using the empirical Bohm formula based on Fick's diffusion law.

The Bohm formula predicts diffusion rates several orders of magnitude higher than the diffusion rate predicted by classical diffusion calculations. This may explain why the magnitude of the diffusion losses was not accurately determined in the 1960s work on ECR plasma acceleration. The reason for the departure from classical theory to Bohm diffusion is not well understood; but it has been suggested that the process is related to plasma instabilities or **E**x**B** drifts. Because Bohm diffusion has been found to give good results over a wide variety of plasma conditions, it is assumed that it is sufficiently accurate to model the transport of plasma across the magnetic field in ECR plasma acceleration.

The approximate time over which the plasma is accelerated down stream in ECR plasma acceleration can be estimated based on the average velocity of the plasma, v_{av}, and the characteristic distance over which the plasma is accelerated, L:

$$\tau_A \approx L/v_{av} \qquad (10)$$

The average plasma velocity is related to the electron energy and the atomic mass of the ions according to the approximate expression:

$$v_{av} \approx [KT_e/(2M)]^{1/2} \qquad (11)$$

Combining terms,

$$\tau_A \approx L[(2M)/KT_e]^{1/2} \qquad (12)$$

If L is assumed to be approximately twice the radius of the accelerator (an assumption which is consistent with previous accelerator designs) the characteristic time for diffusion can be directly compared to the characteristic time for acceleration:

$$\tau_B/\tau_A \approx 2.8eRB/(KMT_e)^{1/2} \qquad (13)$$

For effective operation of this device, it is desirable to have $\tau_B/\tau_A > 1$. If this condition is not met, a significant fraction of the plasma energy could be lost to the accelerator wall via radial diffusion.

The ECR plasma accelerators which were tested in the 1960s operated at $\tau_B/\tau_A < 1$. Hence, these devices could not have been expected to yield high efficiency. As the plasma was produced and the electrons energized, a significant fraction of the plasma diffused across field lines to make contact with the wall of the accelerator. Therefore, a significant fraction of the ionization and excitation energy required to produce the plasma was lost to the accelerator wall, along with any useful kinetic energy or electron thermal energy the plasma had acquired. This explains why most of the measured thrust efficiencies of the early devices were in the range of 10 percent.

An analysis has been completed which also accounts for the presence of a sheath in limiting the diffusion losses in ECR plasma acceleration. The details of this analysis will not be reproduced here. It was found that the formation of a sheath has only a small effect in reducing wall losses because the electron temperature and hence the ion acoustic velocity is high enough to allow the plasma to move freely across the sheath to the wall.

Discussion of Preliminary Theory

The scoping calculations presented above represent a preliminary theory of ECR plasma acceleration. The purpose has been to provide the ground work for the development of a more rigorous, unified theory of this process. Based on these calculations, it is expected that the planned research device will produce thrust efficiencies of approximately 50 percent. Elastic scattering of electrons in the acceleration process is expected to account for the largest portion of energy losses in this device. Other significant loss mechanisms are expected to include inelastic collision processes and cross-field diffusion.

V. Application to Spacecraft Propulsion

When ECR plasma acceleration is applied to spacecraft propulsion, any suitable microwave source can be used as the power supply. This process has the potential to operate as part of an electric propulsion system, in beamed energy propulsion, or in fusion propulsion. These potential applications of ECR plasma acceleration are briefly described in the ensuing discussion.

Desirable attributes of an effective propulsion technology include: (1) high thrust efficiency, (2) flexibility to operate throughout a specific impulse range appropriate to missions of interest, (3) unit power handling capability well matched to available power supplies, (4) simplicity, (5) reliability, (6) long life, and (7) flexibility to use propellant fluids which are inexpensive, easily stored, readily available, and safe. All existing electric propulsion technologies require compromises on these attributes. For example, electrostatic ion thrusters promise long life and high efficiency, but are not well suited to operation at the relatively low specific impulse appropriate to Earth-orbital missions. By contrast, electrothermal arcjets can operate effectively at lower specific impulse and with less exotic propellants, but suffer from relatively low thrust efficiency and limited life.

Electric Propulsion

An electric propulsion system based on ECR plasma acceleration could avoid some of the performance compromises which limit existing electric propulsion technologies. When fully developed, this process can potentially be made to operate at thrust efficiencies comparable to those of electrostatic ion thrusters throughout a range of specific impulse that encompasses the traditional domains of both thermal and electrostatic devices. The electrodeless nature of this process suggests that ECR thrusters may possess an inherently long life and be capable of processing a wide variety of propellant fluids. Based on present understanding, power handling capability per unit is expected to be limited by cavity wall losses (which depend on the ratio of the surface area of the plasma to its volume) to a minimum of approximately 100 watts. In principle, maximum unit power handling capability is limited only by available microwave power. Conceptual designs have been proposed for ECR devices operating at unit power levels as high as several gigawatts.[16]

An important component of an electric propulsion system based on ECR plasma acceleration is the required microwave source. Limitations on the efficiency and specific mass performance of magnetron or klystron microwave supplies were viewed as a significant problem with ECR propulsion when it was first investigated in the 1960s. Technological advancements since the 1960s suggest that a microwave source for electric propulsion can be designed for electric to microwave power conversion efficiencies of 85 to 90 percent, an operational life time of several years, and a specific mass of about 0.5 kg/kW.[17,18]

Before ECR plasma acceleration can become practical for application to electric propulsion, an overall propulsion system design must be produced. In such a design the efficiency of both the microwave source and the thruster are two important parameters. Both the total propulsion system mass and the power lost to the solenoid coils must be considered. Such a system design has not yet been attempted, so information concerning possible system performance is limited. However, approximate calculations suggest that if the recent breakthroughs in the area of superconductor technology lead to appropriate high-field solenoids, which can operate at temperatures at or above the boiling point of nitrogen, total system mass for electric ECR propulsion systems will be less than 1 kg/kW (excluding the primary electric power supply). This impressive specific-mass performance can be accomplished only at power levels of tens of kilowatts or higher.

Beamed Energy Propulsion

Figure 2 shows a conceptual schematic of how ECR plasma acceleration could be used in a beamed energy propulsion system. In this application, a remotely located transmitter would be used to launch a microwave beam toward the spacecraft.[16] On the spacecraft, a parabolic antenna would serve to focus the microwave power into the thruster. This concept would free the spacecraft from the requirement of carrying an expensive or massive on-board power supply to operate at specific impulses now achievable only by a few electric propulsion devices. Because the collector would have to be rather large to effectively capture a microwave beam transmitted over useful distances, a premium would be placed on minimizing the mass density of the collector. One possible approach would be to use an inflated antenna to receive the incoming microwave radiation as shown in Figure 2.

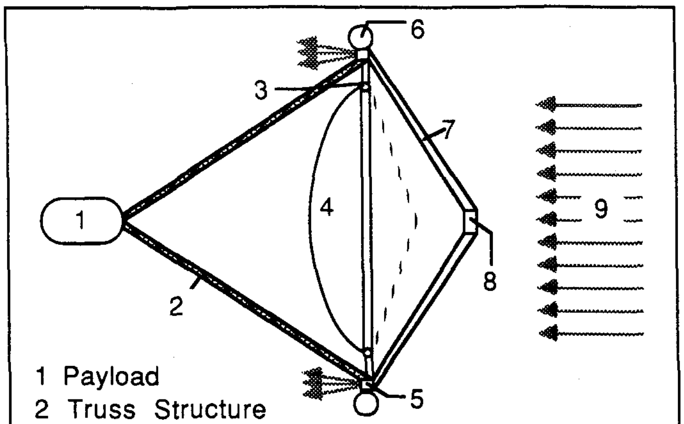

Fig. 2 Concept of Beamed Energy Application of ECR Plasma Accelerator.

Fusion Propulsion

An even more advanced spacecraft propulsion application of ECR plasma acceleration would be its use as a thruster in a propulsion system using a magnetic confinement nuclear fusion reactor as its energy source. Recently, Logan has proposed harnessing the microwave synchrotron radiation that will be produced by magnetic confinement fusion reactors.[19] Analysis suggests that up to two thirds of the fusion power output of a D-He^3 reactor can be extracted in the form of microwave radiation.[19] It is suggested that this microwave power can be coupled out of the fusion reactor cavity via low-loss waveguides.[19] If such microwave power output can be extracted from a fusion reactor, it can then be delivered directly to an ECR plasma accelerator to provide power for an extremely high performance spacecraft propulsion system.

VI. Summary

ECR plasma acceleration is an electrodeless process by which microwave power is converted to directed energy in a flowing plasma. This process can be used in a wide variety of spacecraft propulsion applications. The first such application is likely to be in electric propulsion systems. More advanced applications may include beamed energy propulsion and fusion propulsion. The advantages of ECR plasma acceleration for future spacecraft propulsion stem from its potential for high specific impulse, high efficiency, long life, and the flexibility to use a wide variety of propellant fluids.

The dipole moment body force which acts between an applied diverging magnetic field and the electron motion in a plasma is an efficient mechanism for accelerating the plasma in ECR propulsion. Past researchers have shown that the electron-cyclotron-resonance effect can be used to effectively couple microwave power to an appropriate plasma. A small but non-negligible power loss results from line radiation caused by electron-atom collisions. Losses due to double ion production or incomplete propellant ionization are expected to be important, but not dominant. Devices tested in the 1960s probably suffered from excessive cross-field diffusion losses which can be limited in future accelerator designs.

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