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CONTINUOUS PLASMA ACCELERATION AT ELECTRON CYCLOTRON RESONANCE

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CONTINUOUS PLASMA ACCELERATION AT ELECTRON CYCLOTRON RESONANCE

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ABSTRACT

Experimental and analytical results are presented covering a continuous method of accelerating neutral plasmas. By raising the electron energy selectively in electron cyclotron resonance and transferring this energy to the ions by space charge interaction, plasma beams have been produced at specific impulses and thrusts of interest for space propulsion. In the well collimated plasma beam produced during the preliminary experiments demonstrating the effect, a thrust of 10 dynes/cm^2 was measured by means of a mechanical vane. Mercury ion energies from 50 to 135 ev at densities of 5×10^{10} per cm^3 were measured by means of a retarding potential energy analyzer. Within the present experimental limitations good agreement between theory and experiment was obtained. A substantial increase in thrust density and an increase in specific impulse appears feasible by optimization of the experimental parameters.

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I. INTRODUCTION

This paper is concerned with the acceleration of neutral plasmas. Energy input to the plasma is achieved by selective transfer of rf energy to the electrons through combined magnetic and electric fields at electron cyclotron resonance. With the density in the acceleration region adjusted such that[*] $\omega_{be}\tau > 1$, the mean free path (parallel to the magnetic field) of the electrons between collisions is greater than the Larmor radius (determining the mean free path transverse to B_z). Because of this nonscalar character of the electron mobility in the presence of a magnetic field at low pressures, an electron space charge is set up by the axial electron flux that accelerates the ions axially. No beam extraction potential need be applied. Momentum input to the plasma is thus achieved parallel to the magnetic field. (A somewhat related scheme that depends in its operation on a nonhomogeneous magnetic field was reported previously without experimental results[1].) Indicative of the advantages of selectively working on the plasma electrons is the required low magnetic field at 140 Mc of approximately 50 Gauss, leading to reduced problems in field production and beam extraction from the field.

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[*] Symbols are defined at the end of paper.

As will be shown below in more detail, specific impulse and thrust levels have been measured in experiments to demonstrate the above effect. Values observed are in the range of interest for space propulsion. A broader range of specific impulse values could easily be covered if possible changes of ion mass are also considered. The relevant theory and a description of the preliminary experimental apparatus used to verify the basic concept will be described below, along with density, thrust and ion energy distribution measurements.

II. THEORY

A. Energy Gain of Electrons at Cyclotron Resonance.

To obtain efficient energy transfer to the electrons without appreciably heating the ions or neutrals, use is made of electron cyclotron resonance. Electrons, gyrating at cyclotron resonance in phase with the applied rf field, continuously experience an accelerating field. The mean energy gain of the electrons between collisions at microwave frequencies has been calculated previously[2]. For a homogeneous, time invariant magnetic field B_Z applied at right angles to a homogeneous alternating electric field $E = E_o \cos \omega t$, the mean energy gain of the electron is

$$\bar{W} = \frac{e^2 E_o^2}{4\, m_-} \quad \frac{1}{(\omega + \omega_{be})^2 + \nu^2} + \frac{1}{(\omega - \omega_{be})^2 + \nu^2} \qquad (1)$$

For the conditions of the present experiment, $\omega = \omega_{be}$ at cyclotron resonance and $\omega \gg \nu$ at low pressures, Equation (1) then reduces to

$$\bar{W} = \frac{e^2 E_o^2}{4 \, m_- \nu^2} \, . \tag{2}$$

At a given rf field strength, the only accessible parameter for influencing the final energy of the electron is the collision frequency $\nu = nqv_-$. To estimate the order of magnitude of energy to be expected, the collision frequency ν is assumed to be 10^8 sec^{-1} ($n = 10^{14} cm^{-3}$, $q = 10^{-15} cm^2$ and $v_- = 10^9$ cm/sec) with $E_o = 50$ v/cm. The electron energy is found to be:

$$\bar{W} \cong 100 \text{ ev} \, .$$

It is instructive to compare the mean electron energy gain between collisions at cyclotron resonance (equation 2) with the mean energy gain of electrons at plasma resonance[3] under conditions of applied rf field (and zero magnetic field):

$$\bar{W}_{cycl.} = \frac{1}{4} \frac{e^2 E_o^2}{m_- \nu^2} \tag{3}$$

$$\bar{W}_{pl.} = \frac{2}{\pi^2} \frac{e^2 E_o^2}{m_- \nu^2} \tag{4}$$

Both energy gains between collisions are comparable; however, the cyclotron resonance offers an advantageous method of raising the electron energy for the following reasons: (1) penetration of the

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rf field into the plasma is enhanced at lower applied frequencies; (2) cyclotron resonance is not dependent on a critical density; and (3) the magnetic field necessary to achieve cyclotron resonance simultaneously provides a means of plasma confinement.

B. <u>Space Charge Acceleration and Momentum Transfer</u>.

In the previous discussion the feasibility of raising electron energies to levels in the order of 100 ev was shown. Such energies are suitable for plasma propulsion if energy transfer from the electrons to a collimated ion beam can be achieved. The conditions for such an acceleration of ions by the space charge of the electrons will be outlined below. The reasoning will follow earlier discussions[4,5,6] of the acceleration of a neutralized ion beam by a potential gradient as developed in connection with Penning or oscillating electron discharges.

In the acceleration region, the plasma density can be adjusted to provide various collision frequencies. For the experimental conditions described below, the collision frequency ν was adjusted by varying the temperature of mercury (the propellant) to yield a ν of about $3 \times 10^7 sec^{-1}$. The dominating electron collisions are the ones involving neutrals. With the applied frequency equal to 1.4×10^8 c/sec, electrons gyrate many times before colliding. After collisions, electrons travelling parallel to B_Z in the axial direction (where the mean free path is much greater than a Larmor radius) traverse the rf field region in less than one period of the applied frequency. An axial flux of energetic electrons neutralized by ions at rest is therefore assumed. With the rf electric field supplying energy continuously, the electrons will have a spectrum of energies from near zero to hundreds of volts depending on collision times. The electrons with maximum energy will leave the accelerating volume axially and parallel to the magnetic field thus setting up a space charge potential gradient. The lower energy electrons will be reflected by this potential gradient.

The space charge gradient will cause the ions in the accelerating chamber to be accelerated in the axial direction. Quasi-neutrality can be achieved and a sufficient space charge field maintained to produce a continuous flow of high speed ions and electrons from the accelerating chamber. It is assumed that the electron energy on the accelerator side of the space charge region is much greater than the ion energy and also that the directed ion energy on the output side is much above the electron energy.

It should be pointed out that the ion energy gain from mechanisms other than the described space charge acceleration is negligible. Since ions do not directly gain energy from the high frequency electric field, ion heating could be caused only by collisions with the energetic electrons. However such a momentum transfer is small because of the electron-to-ion mass ratio. The calculated value of ion heating for an interaction time determined by the ion thermal velocity is of the order of thermal energies and can therefore be neglected.

Assuming that there are no other forces acting on the ions (i.e. there are no externally applied extracting fields), the flux of momentum into the space charge region must equal the flux of momentum out of the region. For almost complete reflection of the electrons by the potential gradient, $\frac{nv_-}{2}$ electrons per cm^2 per sec will be flowing back towards the input or accelerator side. With the change of momentum per reflected electron equal to $2\ m_- v_-$, the momentum flux $(n\ m_- v_-^2)$ of electrons reflected from the gradient represents the momentum input into the accelerator region. The momentum efflux $(n\ Mv_+\ v)$ away from the accelerator region is given by the flow of nv ions per cm^2 per sec, each with a momentum of $M\ v_+$.

The momentum flux leaving the space charge region is caused primarily by the high velocity flow of ions. This momentum flux is assumed to have been transferred from the momentum of the very high flux of electrons that is reflected by the potential gradient of the space charge region.

The apparatus described below was geometrically symmetric along the axis of the accelerator and thus plasma beams were emitted from both ends of the apparatus. For this case, momentum is conserved by oppositely directed fluxes. For practical application of the principle however, it should be possible to redirect the reverse flow of momentum. Energy and momentum considerations show that the oscillating electron current in the accelerator region is several orders of magnitude greater than the ion current density. A beneficial contribution of this high current density to the discharge region is a higher ionization in the central region of the accelerator, leading to reduced wall losses.

C. Wall Losses.

In electric propulsion devices, two types of inefficiencies caused by particles lost from the plasma are of prime importance. Rather small fluxes of energetic heavy particles, although not constituting an appreciable direct energy loss, can cause sputtering of up to ten particles per incident ion upon hitting the accelerator structure. The deterioration of the field shaping acceleration electrodes and the concurrent changes in field distribution and focusing properties can then seriously reduce the effectiveness of such a device for long acceleration time applications. In ion engines, it appears to be necessary to limit the interception of ions to less than 10^{-4} to 10^{-5} times the total ion current. For the cyclotron resonance plasma accelerator, this difficulty of electrode and field shape deterioration is taken to be of no concern, since there is no appreciable acceleration of ions at right angles to the axial magnetic field, and, in addition, both the electric and the magnetic fields are insensitive to small changes of the wall surfaces.

A second, different type of inefficiency can be caused by direct energy losses from the plasma due to sufficiently great fluxes of energetic particles impinging on the material walls of the acceleration vessel. To gain insight into this mechanism of energy loss from the plasma, the process of classical diffusion of the electrons has been considered from the point of view of the probability of an electron's reaching the wall of the acceleration chamber. This is a typical random walk problem, where the particle has an even chance to move either towards or away from the wall or out parallel to the magnetic field. Dividing the plasma into concentric rings of a thickness of the order of a Larmor radius, the stepping distance across the magnetic field, the number of particles lost to the wall is found to be:

$$n_L = \sum_i n_i P_i , \qquad (5)$$

with n_i and P_i the number density and probability for reaching the wall from the i^{th} ring. The probability P_m for a displacement equivalent to m unidirectional steps to occur during N steps is given by[7]:

$$P_m = \frac{N!}{\left(\frac{N}{2}+\frac{m}{2}\right)!\ \left(\frac{N}{2}-\frac{m}{2}\right)!}\, p^N . \qquad (6)$$

With $p = \frac{1}{3}$ and assuming the total number of particles in the outer rings to be approximately equal, it is found that only the 3 to 4 outer layers of thickness r_L contribute significantly to the wall flux and that the summation over the probabilities of these outer rings, using Equation (6), is less than 0.5.

$$n_L = n_i \sum P_i < .5\, n_i . \qquad (7)$$

The total loss of electrons from the plasma to the wall is less than 50% of all the electrons n_i in the outer ring thickness r_L. The ratio of energetic electrons reaching the wall to the total number of electrons contained in the plasma is then found to be:

$$R_1 = \frac{r_L}{r_{pl}} . \qquad (8)$$

It is possible then to reduce the energy losses to the wall to a few percent of the input power by making the chamber radius much larger than the electron Larmor radius. No density gradient or any other means of preventing diffusion to the walls has to be introduced. Wall materials with low secondary electron yield should be used in order to maintain a low electron density near the wall. Should Bohm-type anomalous diffusion prevail, loss rates greater by approximately $\omega\tau$ than the ones given above must be expected.

Loss rates due to recombination, cyclotron radiation and Bremstrahlung were found to be negligible and will not be discussed. The number of doubly ionized atoms and the inefficiency due to their acceleration are negligible in the present arrangement. The ratio of the Hg +/Hg++ electron-ionization cross section at approximately 100 ev is close to ten. Since the percentage of ionization of the gas is not high (the dominant collisions are electron-neutral collisions), the flux of Hg++ is expected to be in the order of fractions of one percent of the Hg+ flux. Losses due to Hg-meta-stables at the ^3P_o level (4.66 ev) are estimated to be in the order of 1/100 of the total input power, assuming the number of ions and metastables in the discharge to be equal.

D. Density Limitation Due to Plasma Diamagnetism.

At cyclotron resonance, the electrons gyrate in such a way that according to Lenz's rule the effect of the external magnetic field inside the plasma is reduced. The magnetic moment of the gyrating electrons causes "diamagnetism". In the case of high electron density or energy the reduction of the local magnetic field inside the plasma will be sufficiently high so that the resonance conditions no longer apply. To calculate the limitation on the electron density for a given electron energy we note that the plasma will appear diamagnetic when the energy density of the applied magnetic field approaches the energy density of the plasma and therefore

$$n_{max} \leq \frac{B_z^2}{2\mu_o W} \qquad (9)$$

This leads to the following approximate density limitations:

$\bar{W}$	n	B	f
100 eV	$10^{12}cm^{-3}$	50 G	140 Mc
100 eV	$10^{14}cm^{-3}$	10^3 G	2.4 kMc
10 Kev	$10^{12}cm^{-3}$	10^3 G	2.4 kMc

These limitations appear to be of no serious concern since the densities that can be obtained with no strong diamagnetic effect are quite high. For example assuming only 1% of the electrons given above are at the maximum energy at any time, the following axial flux is obtained for the experimental conditions to be described:

$f = 140$ Mc, $B = 50$ G, $n = 10^{10}$ per cm^3.
$\nu = 10^8$/sec, accelerating chamber length = 1cm.

$$\Gamma_{ax} = 1/3 \; n \nu l \approx 50 \; ma/cm^2.$$

Considering that electrons will also disappear from the axial flow by collisions during the phase of momentum exchange, this result compares well with the efflux of ions measured in the experiments made to date.

Although the energy gain of the electrons does not depend on the applied frequency, higher frequencies appear favorable, since their use permits a significant increase in density. In addition, diffusion may be reduced either according to $\frac{1}{B_Z^2}$ (classical diffusion) or to $\frac{1}{B_Z}$ (anomalous diffusion).

III. DESCRIPTION OF THE EXPERIMENTAL APPARATUS.

The experimental apparatus built to test the principles described above, and shown in Figure 1, consisted of the rf circuitry and power supply, the Hg-vapor source and acceleration vessel, the vacuum system into which the accelerated plasma expanded and the ion energy analyser or thrust indicator. From the gas source vessel on the right side of Figure 1, Hg vapor was introduced into the acceleration chamber located in the rf and magnetic fields. The other end of the acceleration vessel opened into a 6" Pyrex cross. The accelerated plasma expanded into this cross and was analysed at the far end of this chamber. During the experiments the pressure in the expansion and analysis section of the system was kept below 10^{-5} torr.

Rf power at 140 Mc was fed into a coaxial system connected to a parallel-line $\lambda/4$ resonance circuit. The open end of this resonant circuit contained the acceleration vessel, with the rf field applied to the Hg plasma by means of capacitive coupling. Tuning to electron cyclotron resonance was best achieved by adjusting the magnetic field strength for maximum thrust. No external electron source was needed to initiate or maintain the discharge.

The acceleration vessel was located in the homogeneous magnetic field region of a Helmholtz coil. For the case where the coil distance is equal to the coil radius, the field B_Z on the axis near the midpoint r/2 between the two coils is given by:

$$B_Z(Z) = B_Z(r/2) \left[1 - \frac{144}{125} \left(\frac{Z - r/2}{r/2} \right)^4\right], \qquad (11)$$

where $B_Z(r/2) = 50$ G in the present experiment. The coil size was calculated such that at a distance of ± 1 cm from the midpoint $\Delta B < 1.8 \times 10^{-3}\, B_Z\ (Z = r/2)$ and for ± 2 cm from the midpoint $\Delta B < 3 \times 10^{-2} B_Z(Z=r/2)$, i.e., the field in the acceleration region was homogeneous.

Two types of plasma detectors were used, a vane for thrust measurements and a retarding potential plasma probe. The vane consisted of an aluminum disc pendulum which was knife edge supported and friction damped. The plasma probe consisted of a Faraday cup containing a retarding field for the ions and an ion collector as shown in Figure 2. The grid on the input side was connected to ground potential. Since the positive, ion-retarding grid accelerated electrons to the collector, the negative collector voltage was adjusted to an absolute value above that of the (positive) retarding grid and thus reflected electrons to the wall. To prevent low energy electrons from leaving the collector, a secondary electron suppressor voltage was kept 5 v negative relative to the collector. To facilitate fast recognition of changes in the ion energy distribution, the retarding potential was swept from 0-200 v periodically and the collector current versus retarding potential curve was displayed continuously. The collector current signal was electronically differentiated. This final signal provided the ion energy distribution function directly.

IV. EXPERIMENTAL MEASUREMENTS AND RESULTS.

A. Thrust Measurements.

Upon application of the rf power, a well collimated continuous plasma beam emerges from the field interaction region, as shown in Figure 3. Rf fields in the order of 100 v/cm were applied. With the vane a thrust of about 10 dynes/cm^2 was measured. Maximum deflections were observed when the B_Z-field was adjusted for electron cyclotron resonance, e.g., 50 G for a frequency of 140 Mc.

B. Ion Energy Distribution Measurements.

The ion energy distribution in the plasma beam was measured by means of the retarding potential energy analyser described above. Hg ion energies from 50 to 135 ev were measured. Representative oscillograms showing the effect of the retarding field on both the collector current and the differentiated collector current (which yields the ion energy distribution) are given in Figures 4 and 5. The ion energy spread at an axial position located 25 cm from the acceleration region was found to be rather narrow (ΔE at half maximum $= \pm 6\% \, E_{peak}$). The density of the ions in the beam as obtained from the current to the collector and corrected for the beam spread was 5×10^{10} per cm^3. From these data the thrust is calculated to be:

$$Mnv^2 A = 16 \text{ dynes}$$

This result is in good agreement with the direct thrust measurement by vane of 10 dynes.

C. Ion Energy Dependence on Field Strength and Collision Frequency.

The dependence of the ion energy on the rf field strength and on the collision frequency was measured in a qualitative way. No precise calibrations have been performed yet. With these limitations, the measurements of ion energy versus Hg pressure in the acceleration region and versus applied field strength agreed with the theory as given above. For an increase in Hg temperature from 20°C to 22°C, which is equivalent to a density change from 4.2×10^{13} to 4.9×10^{13} particles per cm^3, the ion energy changed from 100 ev to 80 ev for constant rf field. Comparison of this observed energy change with the value calculated from the change in collision frequency shows a deviation of less than 10%.

D. Other Observations.

Visual observations indicated a brighter region in the center of the discharge. This effect is attributed to the high flux of oscillating electrons in this central region.

It was found that at higher rf power-inputs acceleration to similar energies could be obtained without the application of the B_Z field. This is in qualitative agreement with calculated electron energies at higher field-strengths. Density modulations were observed in the case of applied B_Z field, when the magnetic field strength was not adjusted for cyclotron resonance. It might be hypothesized that these modulation frequencies are connected to anomalous diffusion.

V. SUMMARY

Electron cyclotron resonance has been utilized to produce a well collimated plasma beam of energy and density suitable for space propulsion. Although the discharge could be used as an ion source, the present experiment did not require an extraction voltage. Electrons were supplied by the discharge mechanism, thus eliminating the need for a thermionic emitter. Acceleration of the ions is believed to be achieved by means of a space charge field set up by the energetic electrons. Since the ions are at thermal energies, confinement fields are determined by the electron Larmor radius and therefore are relatively small. Analysis shows that at higher applied frequencies and power, rather dense beams in the order of amperes per cm^2 appear feasible. The observed density modulations on the plasma beam indicate the importance of a better understanding of the prevailing diffusion mechanisms in similar devices.

DEFINITION OF SYMBOLS

A Area of plasma beam.

B_Z Axial magnetic field adjusted for cyclotron resonance.

d Coil separation of Helmholtz-coil; equal to coil radius.

E Applied electric field.

E_o Amplitude of applied electric field.

e/m_- Electron charge to mass ratio.

G Gauss.

l Acceleration chamber length.

M Ion mass.

m Number of unidirectional steps.

N Total number of steps.

n Particle number density.

n_i Number of particles in the i-th ring.

n_L Number of electrons lost to the wall.

P Probability for electron to reach the wall.

p Probability for electron to step towards wall after collision.

q Electron-neutral collision cross section.

R_l Ratio of electrons lost to wall to electrons contained.

r_L Larmor radius.

r_{pl} Plasma radius.

v Final plasma velocity.

v_- Electron velocity in acceleration region.

v_+ Ion velocity in acceleration region.

W Average electron energy gained between collisions.

Γ_{ax} Axial flux of electrons.

μ_o Permeability of free space.

τ Time between collisions for electron.

ω Frequency of applied electric field.

ω_{be} Electron cyclotron resonance frequency.

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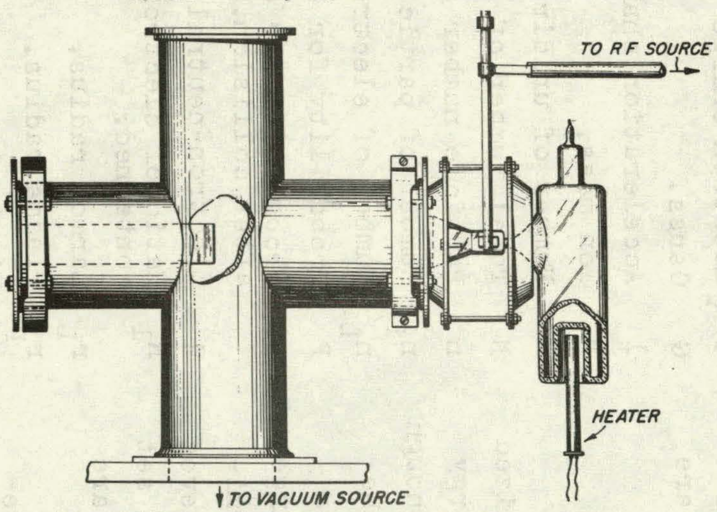

Figure 1. Experimental Apparatus, Electron Cyclotron Resonance Accelerator

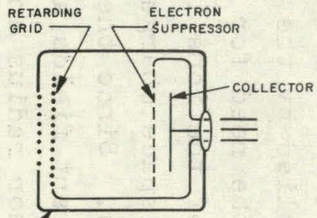

Figure 2. Ion Detector

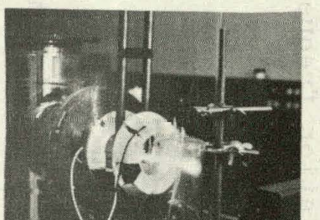

Figure 3. Mercury Beam Issuing from Accelerator Region

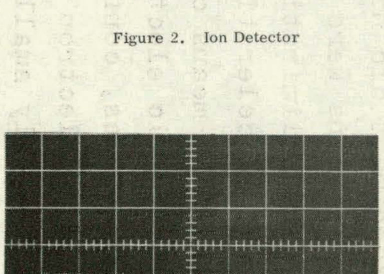

Figure 4. Collector Current Plotted Against Retarding Potential (Ordinate: Relative Units; Abscissa: 12 ev per div.)

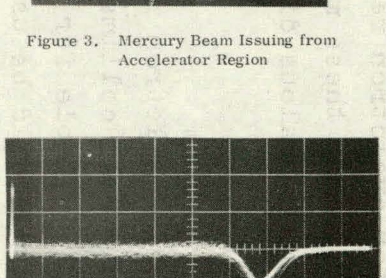

Figure 5. Differentiated Collector Current Ion Energy Maximum at Approximately 80 ev. (Ordinate: Relative Units: Abscissa: 12 ev per div.)