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by Graham Russell, James Litton, and P. B. Myers

Prepared by
BUNKER-RAMO CORPORATION
Canoga Park, Calif.
for Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1966

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By Graham Russell, James Litton, and P. B. Myers

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This final report documents and summarizes the study on hollow cathode plasma penetration conducted by The Bunker-Ramo Corporation for the National Aeronautics and Space Administration, Electronics Research Center. The report is submitted in compliance with the requirements of Contract NAS 12-9.

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I. INTRODUCTION

The objective of this study, conducted under Contract NAS 12-9, was to determine whether the electron beam mode discharge (EBMD) is suitable for penetrating the plasma sheath surrounding a reentering vehicle and providing communications. This discharge was first observed in 1960 and has been investigated since under NASA Contract NASw-714 and the present contract.

The discharge is formed by a conventional hollow cathode with a perforated wall. This configuration will discharge in a mode providing an ion collimated electron beam. The beam is stable over a wide range of pressures and voltage. In addition, coherent microwave radiations from the beam have been observed. These properties make the discharge appear desirable for use in reentry communication.

II. SUMMARY OF STUDY EFFORT, BY STATEMENT OF WORK ITEMS

The contractual Statement of Work sets forth five major items for performance under the contract. These items and summaries of the respective efforts to accomplish them are presented in this chapter.

Item 1: Conduct a survey of the literature to collect the existing knowledge of beam-plasma interactions, electron-beam-produced plasmas and characteristics of reentry plasma sheaths that is applicable to the above stated objective.

The First Quarterly Progress Report and the bibliographies of the Second and Third Quarterly Progress Reports and of this report serve to summarize the results of Item 1.

The literature survey, which was to have been concluded 30 June 1966 according to the original schedule, was extended by mutual consent to cover the entire period of performance of the contract. This was done primarily because the speed with which literature could be assembled and digested was limited by processing time at the reference sources and because a much more extensive body of literature on the subject was discovered than had previously been thought to be available. Several thousand titles were searched, several hundred abstracts read, and more than a hundred complete articles studied and analyzed.

The most important articles, in terms of beam-plasma interaction theories and experimental results, were summarized in Bunker-Ramo's First Quarterly Progress Report, dated September 1965. That report does not contain information from classified sources. A classified addendum to the report will be provided upon request of NASA and upon authorization of the cognizant security agencies. A list of the unclassified titles of classified documents is included in the bibliography of that report. No classified developments of significance were reported in the literature which pertain directly to this contract, with one notable exception; i. e. , the work done by Republic Aviation for Wright-Patterson Air Force Base in a beam-plasma reentry communications scheme. The items of significance to this study resulting from this classified contract were not items of security concern in themselves. Therefore, the First and Second Quarterly Progress Reports summarized the essential features of the Republic Aviation effort which pertain to this study. More detailed information will be provided upon request and authorization by the cognizant security agencies.

The most significant beam-plasma interaction studies covered in this search were the Smullin and Getty experiments in high density hydrogen beam-generated plasmas at MIT, and the nonmagnetically confined beam-plasma interaction studies of Looney and Brown at MIT and those of Drummond and Kofoid of Boeing Aircraft in Seattle.

The first group of studies is highly important because of its basic or fundamental significance. The Looney-Brown and Drummond-Kofoid experiments were primarily important because they explain or report coherent oscillations obtained in the absence of magnetic fields through interaction between electron beams and low density plasmas. This, in turn, is important because it is basically the situation, from the interaction field point of view, which obtains in the hollow cathode discharge.

Item 2: Perform theoretical analysis of the microwave radiation from the hollow cathode electron-beam-mode discharge, as a function of beam current, voltage, and pressure including the analysis of the following characteristics:

(a) Power density spectrum of radiation from the discharge

(b) Radiation patterns of the emitted power

(c) Nature of the radiation mechanism.

The range of pressures and degrees of ionization covered will include those typically encountered in the ionized plasma sheath during the reentry phase of space flights.

This item proved to be the most difficult theoretical job, as might be expected from the basic difficulty of providing precise theoretical descriptions of practical plasma behavior, and because one is dealing here with plasma conditions not of the usual idealized laboratory model. However, an approach was found which to some extent has already been verified. Bunker-Ramo's model of the mechanisms involved is based on the Looney-Brown experiments and the Drummond-Kofoid theoretical approach.

Item 3: Investigate, theoretically, the means of controlling the radiated power and of providing microwave modulation of the beam for use in radiation of microwave telemetry signals, incorporating the results of Items 1 and 2.

For purposes of reporting, results of the effort on this item were combined with the report on Item 2, because modulation methods were found to be inseparable from analysis of the source and characteristics of the radiation itself.

This effort is closely related to Item 2 and was conducted concurrently. The theoretical work eliminated many proposed modulation and control techniques, but further experimental work is required before the results are definitive.

Item 4: Theoretically investigate the penetration of neutral gas and of ionized gas by the electron beam from the hollow cathode electron-beam-mode discharge, incorporating the results of Item 1. Penetrating properties will be studied as a function of gas pressure and percentage of background ionization of ionized gas. The range of pressures and degrees of ionization investigated will include those typically encountered in the ionized plasma sheath during the reentry phase of space flights.

This item was performed primarily through extension of experimental results obtained in interaction experiments between the electron-beam-mode discharge and target plasmas. Some experimental investigations and theoretical treatments of the penetration of neutral gas by electron beams were included.

Item 5: Utilizing the results of Items 1 through 4, estimate the value of the utilization of the electron-beam-mode discharge as a technique for providing microwave telemetry through a reentry plasma sheath. The applicability of this method will be stated as a function of:

(a) Sheath thickness

(b) Density of ions and neutrals in the sheath

(c) Percentage of ionization in the sheath

(d) D-c beam power

(e) RF modulator power.

The effort under work statement Items 2 and 4 contributed the most to the accomplishment of this item. The general findings are that the electron beam will penetrate the ion sheath at the altitudes of interest, but the microwave radiation from this beam is still in question. More definitive conclusions must await further experimentation. The results of effort on this item are reported in detail in Chapter III and summarized in Chapters IV and V.

III. DISCUSSION OF TECHNICAL EFFORT

A. EFFORT OF FIRST THREE QUARTERS

The various significant problem areas encountered during the effort covering the first three quarterly contractual periods are summarized in the subsections which follow. The results of the effort on these problems serve as the basis of the work performance for the final quarter's effort, presented in Section C of this chapter.

1. Focusing

The electron beam produced by the electron-beam-mode discharge has a greater than normal stability and collimation, primarily because the balance between divergent space charge forces and convergent magnetic forces is struck and maintained in the very process of forming the beam. In other words, no abrupt change in boundary conditions is encountered by the beam in the process of passing from its source into the region of neutral or ionized gas surrounding its source. Some theoretical support for this picture has been obtained and reported in the Second and Third Quarterly Progress Reports. However, it is the experiments themselves which speak most eloquently for this point of view. The same beam current densities, velocities, and collimation which one is very hard pressed to achieve through the use of sophisticated magnetic focusing techniques in high vacuums is very easily achieved by the electron-beam-mode discharge.

This self-focusing property of the electron-beam-mode discharge can be used as specified, with carefully designed cathodes, if their heat dissipation is adequate and if their size is not comparable to the dimensions of the sheath surrounding the cathode. The use of the beam alone is feasible for penetrating the reentry-produced plasma sheath down to altitudes at least as low as 100,000 feet, everywhere along the reentry body except at the stagnation region, providing (1) the average velocity of the beam is high enough and (2) there are no electric fields external to the reentry vehicle which are significant compared with the voltage required to accelerate the beam in the preferred direction. It is thought that one may thus expect to keep the electron-beam-mode discharge collimated even through large pressure fluctuations, down to at least 100,000 feet, providing such pressure fluctuations do not occur more rapidly than the frequency with which the space charge-neutralized beam can adjust to a change in neutral particle density.

For most reentry speeds (including that of Apollo) suitable for manned spacecraft reentry, this condition is met. For weapons-type reentry velocities and flight profiles, this condition probably would not be met. For precise limitations on the rate at which pressure fluctuations can occur, experiments specifically designed to determine the limit of the beam's ability to adjust to pressure changes must be performed. These simple experiments can be performed in conjunction with the radiation study recommended in the unsolicited proposal previously submitted to NASA, ERC by Bunker-Ramo and in Chapter V ("Recommendations") of this report.

2. Radiation

A theoretical treatment of the radiation mechanisms of the electron-beam-mode discharge has been achieved in the last two or three months of investigation. This treatment is based upon the Looney-Brown experiment and the Drummond-Kofoid theoretical treatment. This approach was outlined in the Third Quarterly Progress Report and is discussed in considerable detail in Section B of this chapter. To summarize, it has been found that, since the present mode of oscillation from the electron-beam-mode discharge is probably the lowest order, and therefore strongest, mode of oscillation achievable, order-of-magnitude increases in power output or efficiency are not likely to occur. Some increases in power output levels can be achieved, probably, through redesign of the cathode, electron-beam power density increases will tend to be linear with increased power and, therefore, unattractive from the point of view of reducing power and weight required for the reentry system. An experimental program to verify the results of these predictions and to determine quantitatively how much improvement can be expected over the previously observed power levels would be worthwhile.

The EBMD has never been considered to exhibit the Boyd and Gould type of amplification which could provide coherent electrokinetic oscillations which were convertible to electromagnetic oscillations. However, for the sake of completeness and in order to round out the categories described previously, the subject will be discussed in connection with the EBMD.

To obtain amplification of the information or signal energy on an electron beam immersed in a plasma, the signal energy must be available as a space charge wave on the beam, and the beam must have a plasma frequency close to the plasma frequency of the medium modified by the cyclotron frequency in the case of a longitudinal B field focusing for the beam (which is usual).

This B field also provides the anisotropy in the permeativity tensor which gives rise to the capability for unstable growth of space charge waves. The qualitative picture does not require the B field, however, and is given without it, under the assumption that bunching amplitudes are small. The plasma electrons oscillate at a frequency of

$$\omega_{pe} = 2\pi \sqrt{n_e} \times 8{\cdot}9 \times 10^3 \frac{\text{rad}}{\text{sec}}$$

where n_e is the electron density in the plasma. The beam electrons oscillate, while drifting, at a frequency

$$\omega_{pb} = 2\pi \sqrt{n_b} \times 8{\cdot}9 \times 10^3 \frac{\text{rad}}{\text{sec}}$$

where n_b is the beam's number density of electrons. If the electrons of the beam are passing through the plasma medium at a velocity

$$U_o = \sqrt{2e/mV_o}$$

where V_o is the d-c beam velocity

$$(\rho v)_{d-c} = n_e A\, U_o$$

will flow, where A is the beam area, modulated by a current modulation

$$\tilde{\rho} v = \tilde{n}_e A \tilde{U}$$

If one writes total current as

$$I = (\tilde{\rho} + \rho)\,(\tilde{U} + U_o)\,A$$

then

$$J \text{ (current density)} = \tilde{\rho}\tilde{U} + U_o\tilde{\rho} + \rho\tilde{U} + U_o\rho$$

Under the assumption of small $\tilde{U}$, $\tilde{\rho}$, neglecting products in RF quantities yields

$$(\rho U_o + \rho\tilde{U} + U_o\tilde{\rho})$$

Let $\tilde{U}$ be a maximum when $\tilde{\rho}$ is in phase qualitative; then, in a snapshot,

$$\rho\tilde{U} \text{ or } U_o\tilde{\rho}$$

represents the total RF modulation amplitude of a wave which propagates at a group velocity U_o and a phase velocity

$$v = \frac{U_o}{1 - \frac{\omega_p}{\omega}}$$

It must now be assumed that

$$\frac{(\omega_p)^2}{\omega} << 1$$

or the phase velocity will be unsuitable for synchronous interaction between the fast and slow space charge waves $(\pm\omega_p/\omega)$ when distributed interaction occurs in a medium whose phase velocity is simply the d-c beam velocity perturbed by kT/m.

Thus, a half-period of oscillation of the electron beam must see a translation of one space charge wavelength in the medium in order for the phase of the retarding field to be proper for growth. Of course, the retarding field is necessary to reduce d-c beam energy through increased RF oscillation.

The requirement for positive energy growth provides ω_p/ω, and, for synchronism, $\omega_p/\omega = 0.1$. In the EBMD, these conditions are obviously violated except for evanescent waves.

3. Penetration

With respect to the beam itself for penetrating the reentry plasma, it is clear that if the power and weight requirements of the power supply and hollow cathode discharge can be met in a reentry spacecraft, one can, through every region of the reentry body except the stagnation region, produce a collimated electron beam which escapes the immediate and most dense regions of the sheath surrounding the vehicle. In addition, there will be radiation of a coherent nature associated with this electron beam propagating along it, either by virtue of the effect of the electron beam itself upon the permeativity tensor of the target plasma or by the beams simply serving as an antenna which is more resistant to loading and physical attrition effects of the plasma. Modulation of this radiation can in principal be achieved by variations in cathode voltage. It has been found impossible, with Bunker-Ramo's present knowledge, to predict the rate at which modulation can occur, the absolute attenuation which the beam-generated coherent radiation would sustain under such circumstances, and the radiation pattern which emerges from the beam-plasma system except in the most general terms. That is, the radiation would tend to be circularly polarized along the axis of the beam. The effective gain of this antenna, however, must be determined by experiment since ordinary antenna theory does not lend itself to predicting the spatial mode structure of such a system.

B. SUMMARY OF THE FIRST THREE QUARTERS' RESULTS

The efforts of the first three quarters can be summarized under two major headings: modulation studies and beam studies. Modulation studies include the generation, control, and transmission of the EBMD-associated radiation through the reentry plasma. Beam studies include the formation, control, and transmission of the beam through the target plasma.

1. Modulation Studies

In the modulation studies, a classification was made of all of the important beam-plasma or plasma oscillation modes which have been analyzed. This was an attempt to reduce the EBMD-associated oscillations to a small enough class to permit a start upon modifying a valid theory to fit the EBMD.

This approach proved to be fruitful, but it was not very economical of labor or rapid. It did produce a body of knowledge for the labor which will continue to be useful to both Bunker-Ramo and NASA, ERC.

It was shown that the EBMD is not a beam-plasma traveling-wave phenomenon, but a plasma (or beam-plasma, in a broader sense) oscillation phenomenon. The existing mechanisms for conversion from electromechanical to electromagnetic oscillations are inappropriate to describe the conversion in the EBMD. The mechanism that is operative has proved difficult to describe.

The frequency-shifting of the output radiation by voltage control of the cathode, observed experimentally, has an explanation of one sort in the sheath-type oscillations or in the plasma diode oscillation described by Wehner et al. The mathematics involved in an attempt to describe the oscillation in the cathode proved by ballistic analysis are intractible.

The analysis, however, did reveal the very significant effect of the electron's acceleration through the sheath and showed that only an extremely non-Maxwellian velocity group can account for the formation of the beam from the negative glow. Previously, spectroscopic studies had provided the same conclusion without providing an insight into the effects of the various portions of the discharge. The line-spectrum nature of the emission, its stability with respect to most discharge parameters (except voltage), and its low power density relative to the discharge energy are consistent with what is understood of the Wehner type oscillations. Coupling the coherent electron oscillations into the beam as space charge waves or into the cathode fields as electromagnetic waves, however, is not likely in the former case, nor quantitatively supported in the latter. It is necessary to experiment further in order to clarify this problem. Such experimentation is provided for in the proposal previously submitted to NASA, ERC.

Considerably more effort is needed in the entire field of radiation mechanisms. There is a plethora of experimental reports of oscillations and radiations in high density, low density, cool, hot, confined, free, accelerated, drifting, gaseous, liquid and solid-state plasmas. There is a respectable amount of generalized energy-momentum-propagation theoretical treatments, with a few allusions to the experiments as classes of events. However, there is nowhere, except in Smullin and Getty et al, a concerted attempt to relate specific observations with nonparametric theoretical treatments.

2. Beam Studies

Considerably more success was met in the beam studies, because there is a history of investigation of beam scattering and collimation running back to J. J. Thompson, or even to Faraday, if one wishes to stretch a point slightly. Many of the most brilliant experimental physicists and mathematical physicists of the nineteenth century and the twentieth century (to 1940) have concerned themselves with this problem. In addition, many of the modern-day engineers concerned with beam tube and ion engine design have used the results of these scientific studies in their analyses of beam formation and control.

There is one factor in the EBMD which has escaped previous attention by investigators prior to the work of Hugo Van Paassen and Emil Muly, in which one of the authors of the present report was involved. This factor is, obviously, the mechanism by which the perforated wall hollow cathode can produce, stably and consistently, a collimated beam in normally hostile regimens of pressure and pressure changes. The explanation is provided, albeit without sufficiently tutorial introduction, by the final report in Contract NASA-714. This tutorial was partially provided in PR No. 3 under NAS 12-9. G. Russell has provided further analysis through a trajectory treatment interior to the cathode, which adds to the realization of the uniqueness of the effect but does not make the tutorial part of the job less difficult. His work is covered in the fourth quarter's effort. Application of the effect to plasma sheath penetration is straightforward for the model of the plasma used. Lack of knowledge, however, exists about the quality of the model which is invincible to those not privy to exact descriptions of the actual reentry plasma — and this large group includes the present investigators, in spite of their studying many reports of measurements and analyses thereof. Fields of large average values transverse to the motion of the beam electrons, or oscillations which derive their amplitude gain from the beam's kinetic energy, are inimical to collimation. Nothing has been found in the present research which can do more than compensate for these perturbations by increased electron velocity. Increases in electron velocity are limited by cathode heat dissipation at high pressures (>10 μ) and by relativistic nonadiabatic effects at low pressures. Since use of the beam in transmission through the plasma sheath is, in practice, power and weight-limited, the latter of these two limitations is academic and the former of concern mainly in the laboratory, or below 100,000 feet.

The period of space charge amplifying oscillations must be, in general, restricted to values of times greater than that required to provide ions to combat the space charge spreading produced thereby (through reduction of beam velocity). Similarly, pressure fluctuations of given magnitude relative to total pressure must occur in periods shorter than the same ion build-up time. Since the only provider of proper ions is the electron beam-air molecule inelastic collisions, the problem reduces to one of neutralizing the excess electron density. If this scattering or collimation takes place in a plasma, such as the reentry plasma instead of in a neutral gas, it can validly be assumed, in the absence of fields, that the plasma electrons space-charge neutralize the ambient ions. This ion build-up time can be expressed in terms of pressure, electron velocity, and ionizing cross-section* as the solution to

$$\frac{dn_2}{dt} = \rho P_{n1} v_1$$

where n_2 is the ion density, n is the electron density, v is the electron velocity, ρ is the pressure and P is the ionizing efficiency. Thus the equation is a statement of balance between electron build-up and ion compensation. Unfortunately, P and v_1 are dissimilar functions of voltage. If one assumes, however, that in a cylindrical beam, N_2 (the total ion density) is the simple average sum of the local densities — so that distribution is uniform spatially — the specific value of t from the equation above may be written as

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*A. Von Engel and M. Steenbeck, <u>Elektrische Gasentladungen</u>, J. Springer, Berlin, Vol. 1, 1932, and Vol. 2, 1934

$$\tau = \int_0^t dt = \int_0^{n_1} \frac{dn_2}{\rho \, P_{n1} v_1}$$

If, further, $N_0 \gg N_2$ or N_1, ρ is not time dependent during the interval, and

$$\tau = \frac{\sqrt{\frac{m}{2e}}}{\rho \gamma \, P_{n1} \sqrt{V}} \int_0^{n_1} dn_2 = \frac{\sqrt{\frac{m}{2e}}}{\rho P \, \sqrt{V}}$$

for τ in μsec, ρ in mm Hg, and P in cm^{-1}.

Note that either n_2 nor n_1 is explicitly contained in this expression, having been integrated out in the case of n_2 and conditioned out in the case of n_1. Thus, the final expression is independent of current for currents small compared with total neutral-plus-ion flux, and for velocities small compared with

$$C, \left(\frac{v}{C} < 0.1\right)$$

Typical values of τ for air are, at 5000 volts: 1 μsec at $P = 10^{-5}$; 0.1 μsec at $P = 10^{-4}$; 0.015 μsec at $P = 10^{-3}$; 0.0012 μsec at $P = 10^{-2}$; etc. Therefore, at pressures in excess of 10 μ, if $\tau < 10^{-3}$, 1 kmc oscillations in pressure can be compensated for if

$$\left(\frac{\Delta n_0}{N_0} \ll 1\right)$$

and the space charge density is

$$\left(\frac{\Delta n_1}{N_1} < 0.01\right)$$

For a Mach 3 passage from 110,000 to 100,000 feet, one observes, outside the region where $P/P_o > 1.0$, a pressure change of 0.15 mm Hg in 10^7 μsec. The conditions are clearly met up to Mach 10 and above. Assume that a stagnation pressure ratio of 20 to 1 is reflected in pressure versus altitude changes as well, so that 0.15 mm Hg

$$\left(\frac{P}{P_o}\right) = 20 \times 0.15 = 3 \text{ mm Hg}/10^7 \ \mu\text{sec}$$

By extrapolation, 1 mm Hg $\approx 10^{-5}$ µsec. The ratio is then

$$\frac{10^{-5} \times 3}{10^{7}} = 3 \times 10^{-2} << 1$$

and is acceptable.

Noting that velocities of translation through a plasma lower than ion thermal velocities provide no net average potential changes, one can validly assume that average potential changes for a material of finite relaxation time, e. g. ,.

$$r = \sqrt{\frac{K}{\sigma}} \leq 22.3$$

for glass fiber phenolic can be no larger than sheath potentials at the surface, or values of 10 to 100 volts, compared with more than 5000 volts accelerating potential.

Penetration of the plasma by the beam is concluded to be practicable based upon experiments with the EBMD and Bunker-Ramo's model of the reentry plasma. However, nothing in the effort of the first three quarters has provided a quantitative picture of the character and amount of controlled radiation which can be associated with the EBMD in the plasma sheath. The fourth quarter's work, as described in Section C of this chapter, does provide a better insight into the radiation mechanisms and overall probability of plasma sheath penetration feasibility. However, it does not provide final answers. These must await completion of experimental investigations recommended in Bunker-Ramo's unsolicited proposal for extension of the present contract, as modified in the Statement of Work.

C. FINAL QUARTER'S EFFORT AND RESULTS

The work of the final quarter has been devoted primarily to developing a model of the mechanisms giving rise to coherent microwave radiations from the EBMD. Earlier work on this contract indicated that the oscillations are a sheath-drift-sheath type of oscillation rather than a spatially continuous interaction between the beam and the plasma. Based on this, the interactions between various regions of the EBMD were investigated to determine where sheath-drift-sheath oscillations could occur. The work of Wehner (Ref. 1) and Looney and Brown (Ref. 2) indicates that the requirements for oscillations of this type are much like those for a klystron. A coherent velocity modulation is imparted to electrons in a sheath, converted to density modulation in a drift region, and removed by a second passage through a sheath. If the following necessary conditions are met, oscillations of this type are possible.

(1) The time an electron spends in the sheath must be consistent with attaining a coherent velocity modulation at the oscillating frequency.

(2) The time the electrons, considered as a group or flux rather than individually, spend in the drift space must be consistent with that required for a portion of their average energy to be available at the oscillation frequency.

(3) A path must be available for the demodulated electromagnetic energy to coherently influence the modulating sheath.

These conditions are not sufficient to ensure oscillation, but since they are necessary they may be used to determine where oscillations of this sheath-drift-sheath type could occur.

This section of the report will first consider applying these conditions in general to the discharge, then examine each in more detail as applied to the model which evolves. Most of the regions of the EBMD discharge do not have the basic configuration required and may be quickly dismissed from the basic model. If the beam is being modulated (as it exits the cathode) by the cathode sheath, this modulation is not likely to be part of basic oscillation mechanism because no demodulating mechanism is apparent downstream on the beam. The collimating plasma-frequency and the beam plasma-frequency were previously shown to preclude a transfer of electrokinetic to electromagnetic energy in the beam region; also, no suitable sheath is apparent for sheath demodulation.

The only region of the EBMD in which this type of mechanism is likely to be operative is interior to the cathode glow. Here electrons in a reasonably field-free region are surrounded by a sheath. If this region meets the three necessary conditions previously stated, a model of the microwave oscillating mechanism similar to Wehner's is indicated.

The first condition may be stated mathematically as

$$\tau = nT + \Delta T \quad (n = 0, 1, 2 \cdots)$$

Where τ is the time an electron spends in the sheath, T is the period of the oscillation, and n is an integer.

With sheath voltages and thickness in the EBMD discharge, the only case of interest is the $n = 0$ case

$$\tau = \Delta T$$

If $\Delta T/T$ is a small fraction, the time coherence of the velocity modulation is ensured.

This type of velocity modulation was reported by Gabor et al (Ref. 3) in 1955. It was observed during measurements of the sheath surrounding the positive column of an Hg discharge using an electron beam probe. These experiments also indicated that the potential distribution in the sheath may be taken as parabolic. Using this result, τ may be written as

$$\tau = \int \frac{dx}{v}$$

where the integral is taken over the electron's path in the sheath, x is the distance from plasma into the sheath, and v is the electron's velocity. The potential in the sheath (V) is

$$V_{(x)} = \frac{V_s}{d^2} x^2$$

where V_s is the sheath voltage drop and d is the sheath thickness. The expression for τ then takes the form

$$\tau = 2 \int_0^{\frac{V_o}{V_s} d^2} \frac{dx}{\sqrt{\frac{2e}{m}} \sqrt{V_o - \frac{V_s}{d^2} x^2}}$$

and finally

$$\tau = \sqrt{\frac{md^2}{2eV_s}}$$

which is independent of V_O, the initial energy of the electron, τ is plotted in Figure 1 as a function of d with V_s as a parameter. From this plot it may be seen that for V_s = 500 V and a sheath thickness of 1 mm, the EBMD conditions, τ is well within the region where the modulation is coherent.

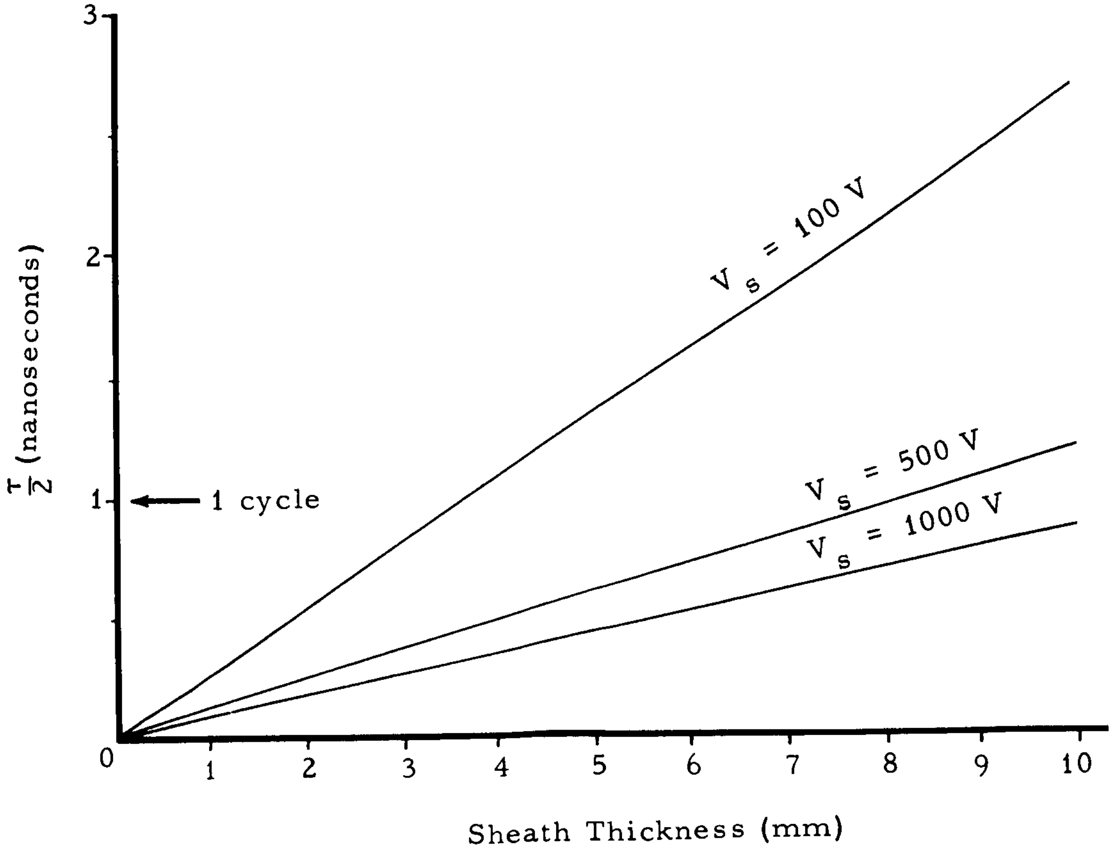

Figure 1. Electron Time in the Sheath as a Function of Sheath Thickness

The second condition is that the electrons, after being velocity modulated, remain in a field-free region the proper length of time for the velocity modulation to be converted to density modulation. The expression for the proper time (t) is given by Wehner as

$$t = \frac{T}{4}(4n + 1)$$

where n is a mode number and T is the oscillation period. For the observed frequency of approximity 1 kmc

$$t = \begin{cases} 1.25 \times 10^{-9} & n = 1 \\ 2.25 \times 10^{-9} & n = 2 \\ 3.25 \times 10^{-9} & n = 3 \end{cases}$$

etc.

For electrons which have the energy of the cathode sheath, approximately 500 eV, the transit time on a diameter of the cathode glow (3 cm) is 2.25 nanoseconds, which corresponds to a mode number of two. At a pressure of 10 μ, the mean-free path of a 500 V electron is approximately 5 cm or on the order of the cathode diameter. This indicates that electrons in the cathode can remain ordered in time and space long enough to deliver 1 kmc energy across the cathode glow.

The condition (third) for feedback between the modulation and demodulation regions may be satisfied if the cathode glow is considered a dielectric sphere. The dielectric constant of the sphere (ϵ) at the angular frequency (ω) is given by

$$\epsilon = \epsilon_o \left(1 - \frac{\omega}{\omega_p}\right)$$

where ω_p is electron plasma frequency. At a number density of 10^{13} electrons per cubic centimeter, ω_p is 3.7×10^9 cps, so that

$$\epsilon = \frac{26}{27}\epsilon_o$$

The effect of this sphere in a cylindrical metal cavity pierced by an electron beam on the normal natural modes of oscillation has not been resolved. The spacings involved are too small for TE or TM modes (Stratton, Ref. 4) but should support degenerate TEM modes. Experimental determination of the mode patterns in the cathode will be required to effectively solve this problem.

The resulting model of the source of oscillations is the cathode sheath modulating the fast electrons in the cathode which deliver some of their kinetic energy to the oscillation due to density ordering which occurs in the cathode. This energy is extracted as electromagnetic energy by the sheath in a region opposite the modulation region. The phasing is maintained by an electromagnetic transfer between the interaction region of the sheath.

IV. STUDY CONCLUSIONS

The conclusions of the program have been reached, with the following general results and comments held to be valid, based upon the investigations reported in Chapter III.

1. Source of Electromagnetic Energy

The beam-plasma interaction studies have shown conclusively that, while beam-plasma amplification of the beam's plasma-electron oscillation is clearly feasible in the positive column, the observed frequencies do not correspond to those which would be so produced. Therefore, as previously conjectured, the cathode region is the source of electromagnetic oscillation. The process by which the thermal and plasma kinetic energy of the negative glow-sheath-cathode regions is connected to coherent electromagnetic oscillations in the microwave spectrum and coupled out is now fairly well understood, in terms of Wehner or Looney-Brown type of oscillations. No purely theoretical treatment of such complex interactions is ever likely to be complete, however, and experiments must be conducted to confirm the model and make it more quantitative. On the other hand, these experiments can now be carefully directed and can be much more economical of time and labor, as well as equipment, since the source region and mechanism have been identified.

2. Communication Through the Plasma Sheath

Among the characteristics of the EBMD-associated radiation, as observed in previous experiments, is the low-power density in the microwave lines. It had been hoped that more of the total discharge power, which is large, could be converted to electromagnetic energy in this frequency region when the mechanism of the source oscillation was found and quantitatively analyzed. Inherent in the process of converting electron vibrations into coherent radiation is a gain of energy proportional to $(\Delta n)^2$ where Δn is the increase in number of electrons oscillating in the proper coherent mode. It has now been discovered that increases in total power in the discharge and not in single cathode or beam geometry changes will probably be required, since the numbers of electrons in the appropriate velocity ranges to affect oscillations are fixed at constant temperature and voltage. Thus, either voltage changes or kinetic temperature changes, resulting in higher power discharges, would be required, to first order, although some cathode transparencies and voltages would be more conducive to larger oscillation amplitudes than others. No orders-of-magnitude increases will result, however, from small variations in discharge parameters, and one must consider the total radiation power output limited by plasma discharge power input.

Enough feasibility exists for the beam's penetration of the reentry sheath and its providing a waveguide to the outside of the high density regions of the plasma to make it worthy of consideration as an antenna or as a means of obtaining a beam for other sheath-penetration techniques. These effects may be considered as modifying the permeativity tensor of the plasma to reduce the critical frequency along the beam's path. However, not enough power from the EBMD can be obtained in the right frequency range to justify checking the effects of other factors.

Unless, in the course of the experimental work to confirm the present pictures of radiation sources, a development occurs which indicates that another, more efficient mode of interaction is present, EBMD penetration of the plasma sheath is not considered to be feasible.

3. General Program Results

It is not surprising that a purely theoretical program and literature search has not produced quantitative answers to questions which had been formulated on the basis of unexpected experimental observations (insufficiently complete to provide data for more than the immediate observer's satisfaction). More than this can be accomplished, however, based upon the year's effort, with much less experimental effort than was formerly required and, in terms of overall expense, with less money. A model has been provided for the radiation mechanism in which considerable confidence is warranted, and which can be used effectively and quantitatively to guide future experiments. Also, a respectable body of knowledge in beam-plasma interactions and the problems of plasma sheath communications has been assembled which will be useful as an annotated bibliography to future investigators and to the current investigators in future programs. NASA's chief benefit will have been the acquisition of this information and a confidence level in beam-plasma penetration methods. A significant and laudable achievement, scientifically, can now be completed in a short experimental program guided by the results of the present program.

V. RECOMMENDATIONS

It is recommended that NASA follow the experimental program in the previously referenced proposal submitted by Bunker-Ramo as a conclusion to the EBMD investigation which began under IRD sponsorship in October 1960, and under NASA sponsorship in January 1963. This proposed program will result in definite, quantitative, and complete descriptions of the EBMD coherent radiation when combined with the experimental results under Contract NAS 714 and the study results under Contract NAS 12-9. It is not recommended that experiment demonstration of the feasibility of plasma sheath penetration be funded because, while such an effect on laboratory scale would probably result, the achievable power levels make it impractical for actual flight use.

Basically two modes of electron beam-plasma interaction can give rise to the observed radiation: (1) the Wehner-type oscillations, and (2) traveling-wave beam-plasma interactions. The former is considered to be the type operative in the EBMD, while the latter is possible between the EBMD and its positive column. These traveling-wave interactions are generally described in the paragraphs which follow, and contrasted with those of the EBMD, so that confidence can be felt in dismissing this type of oscillation mechanism for application to the EBMD.

Among the many investigations of traveling-wave beam-plasma interactions, three emerge as archetypical:

(1) Backward-wave interactions (Hopson et al)

(2) Forward-wave amplification (Boyd and Gould)

(3) Multi-modal beam-plasma interactions (Smullin and Getty).

A good case can be made for including other investigations in this listing, such as the Penning discharge amplifier (Russian), the Drummond-Kofoid observations, and those described by Kino et al. However, the observations as included in the three models listed are believed an adequate grouping for this study.

The dispersion equations which are derived from the propagation equations for waves in plasmas are, in general, implicit functions of the various plasma frequencies ω_0, ω_p, ω_{pb}, ω_c, ω_{pi}, γ, T_e, T_i and tube spacing and voltage parameters. One can look for growing instabilities by inspecting the equations when they are simple enough, but rarely are they so simple. One usually plots the propagation constants versus frequency (normalized to ω_p) for the beam-plasma system. These plots are known as Brillouin diagrams. If a Brillouin diagram has certain topographical characteristics, it is considered a candidate for growing instabilities, and the regions wherein there are slow and fast or negative and positive energy waves coupled closely together are explored more carefully by computing interaction impedances between those possibly unstable modes of coupled waves. This computation is most effectively done (the possible modes best identified) when experimental points of observed oscillations are plotted on the same Brillouin diagram.

When ω_c is identically zero, as in the case of the EBMD, not all formulations of the dispersion equations are equally valid. Sometimes one can substitute $\omega_c = 0$ and obtain correct results, but more often ω_c must exist, no matter how small, in order for the approximations to be valid.

In the case of the Smullin and Getty observations, the interaction is apparently a cyclotron resonance between noise currents at first, followed by an increasingly large local ω_p until the beam's $\omega_{pb} = \omega_p$. The resulting excessive RF fields cause nonlinear transverse fields set up by the interaction on the exis, terminating in rapid heating of the plasma, beam instability, and the production of X-rays, UV light, and highly energetic secondary electrons. Without magnetic fields and ω_{pb} ω_p, these interactions cannot occur, and they are therefore not members of the EBMD set.

Backward wave interactions occur between waves on a beam and waves in a plasma medium in both beam-generated and non-beam-generated systems. The existence of a wave which grows while propagating in a direction opposite to that of the positive energy flow implies the existence of a conductivity or permeativity tensor whose determinantal equations (secular equations) allow for positive feedback of the traveling wave's energy through interaction with the plasma medium. In order to oscillate, this feedback must not only overcome normal system losses, but also the removal of energy from the wave in the normally forward direction by the space charge waves on the beam. There is, therefore, a "start oscillation" current or impedance condition which must be met. The only mode of positive feedback available to an electron beam whose energy is all in the forward direction in a quasi-stationary plasma medium is the backward-wave interaction. The force equations in the presence of a longitudinal field contain terms in both $-V_{x,y} B_z$ and $+V_{x,y} B_z$; however, since there is no external magnetic field in the EBMD system, no backward-wave interaction can exist at any value of current below relativistic velocities for the beam electrons.

VI. REFERENCES

1. G. Wehner, "Electron Plasma Oscillation," Journal of Applied Physics, Vol. 22, No. 6, p 761, June 1951.

2. Duncan H. Looney and Sanborn C. Brown, "The Excitation of Plasma Oscillations," Physical Review, Vol. 93, No. 5, p 965, March 1, 1954.

3. D. Gabor, E. A. Ash, and D. Dracott, "Langmuir's Paradox," Nature, Vol. 176, No. 4487, p 916, November 12, 1955.

4. Julius Adams Stratton, Electromagnetic Theory, McGraw-Hill Book Company, Inc., pp 554-558, 1941.

VII. BIBLIOGRAPHY

1. V. I. Aksenov, "On the Propagation of Electromagnetic Waves in a Magnetoactive Plasma at Below the Plasma Frequency," 22nd Convention on Physical Electronics, March 1962.

2. M. A. Allen and G. S. Kino, "Interaction of an Electron Beam With a Fully Ionized Plasma," Physical Review Letters, Vol. 6, No. 4, p 163, February 15, 1961.

3. G. August, "Plasma Confinement of Electromagnetic Waves," AD 277373, Electronics Research Laboratory, University of California, Berkeley, California, August 1961.

4. M. P. Bachynski, "Electromagnetic Wave Penetration of Re-entry Plasma Sheaths," NBS Report, Radio Science, Vol. 69D, No. 2, p 147, February 1965.

5. M. P. Bachynski and K. A. Graf, "Electromagnetic Properties of Finite Plasmas," RCA Review, Vol. 25, No. 1, p 3, March 1964.

6. D. E. Baldwin, "Electron Overtaking as a Cause of Instability and Type III Solar Radio Bursts," AD 612224, Physics Letters (Holland), Vol. 12, No. 3, pp 202-203, October 1, 1964.

7. David E. Baldwin, "The Effect of Close On the Two-Body Distribution Function in a Plasma," Report No. 402, Massachusetts Institute of Technology, Research Laboratory of Electronics, Cambridge, Massachusetts, May 1962.

8. G. Bedkefi, J. P. Coccoli, E. B. Hooper, and S. J. Buchsbaum, "Microwave Emission and Absorption at Harmonics of a Warm Plasma," Physical Review Letters, Vol. 9, No. 1, p 6, July 1, 1962.

9. I. B. Bernstein, "Waves in a Plasma in a Magnetic Field," Physical Review, Vol. 109, No. 1, p 10, January 1, 1958.

10. E. J. Blau, "An Annotated Bibliography on Plasmas in Cusped Magnetic Fields and Similar Geometrics," AD 451426, TG 230-B-4, Applied Physics Laboratory, Silver Spring, Maryland, August 1964.

11. D. Bohm and E. P. Gross, "Theory of Plasma Oscillations, B, Excitation and Damping of Oscillations," Physical Review, Vol. 75, No. 12, p 1864, June 15, 1949.

12. M. H. Bortner, "Shock Layer Electron Densities Considering the Effects of Both Chemical Reactions and Flow Field Variations," Planetary and Space Science, Vol. 3, pp 99-103, February 1961.

13. G. D. Boyd, L. M. Field, and R. W. Gould, "Excitation of Plasma Oscillations and Growing Plasma Waves," Physical Review, Vol. 109, No. 4, p 1393, February 15, 1958.

14. G. D. Boyd, R. W. Gould, and L. M. Field, "Interaction of a Modulated Electron Beam With a Plasma," Proceedings of IRE, Vol. 49, p 1906, December 1961.

15. S. J. Buchsbaum, "Ion Resonance in a Multicomponent Plasma," Physical Review Letters, Vol. 5, No. 11, p 495, December 1, 1960.

16. S. J. Buchsbaum and S. C. Brown, "Microwave Measurements of High Electron Densities," Physical Review, Vol. 106, No. 2, p 196, April 15, 1957.

17. S. J. Buchsbaum, L. Mower, and S. C. Brown, "Interaction Between Cold Plasma and Electromagnetic Waves," Physics of Fluids, Vol. 3, No. 5, p 8061, September 1960.

18. O. Buneman, Radiation and Waves in Plasmas, Stanford University Press, 1961.

19. R. G. Buser and P. Wolfert, "Microwave Interaction With Plasmas," IRE International Convention Record, Vol. 8, Parts 1-3, p 146, 1960.

20. Howard Chang, "The Hose Instability of a Finite, Pinched, Relativistic, Electron Beam Penetrating an Infinite, Field-Free, Temperate Plasma," Technical Report 201, Stanford Research Institute, September 1963.

21. W. S. C. Chang, "Memorandum on Electromagnetic Properties of the Hypersonic Plasma Sheath," AD-240, 445, Report 786-29, Ohio State University Research Foundation, Antenna Laboratory, Columbus, Ohio, June 30, 1960.

22. Z. S. Chernov and G. Bernaskevsky, "Resonance and Fluctuation Phenomena Accompanying Microwave Amplification in the Plasma Electron Beam System," 22nd Convention on Physical Electronics, March 1962.

23. J. D. Cobine, Theory and Engineering Applications of Gaseous Conductors, Dover, 1958.

24. B. Coppi, "Addendum on Inertial Interchange Modes," AD 612225, Physics Letters (Holland), Vol. 12, No. 3, p 213, October 1, 1964.

25. F. R. Crownfield, "Microwave Cavity Measurement of the Faraday Effect in a Glow Discharge Plasma," Fourth NASA Convention on Plasma Physics, December 1963.

26. R. L. Daniels, "Methods of Approximating the Ion Field Surrounding Advanced Missiles," AD-236-932, Air Force Cambridge Research Center, Bedford, Massachusetts, 1960.

27. P. C. T. DeBoer, "Velocity Modulation of a Relativistic Electron Beam," Journal of Applied Physics, Vol. 35, No. 35, p 2789, October 1964.

28. J. L. Delcroix, Introduction to the Theory of Ionized Gases, Interscience Publishers, Inc., New York, 1960.

29. H. Derfler, "Theory of RF Probe Measurements in a Fully Ionized Plasma," Proceedings of Third International Conference on Ionization Phenomena in Gases, Munich, 1959.

30. E. G. Dirsa, "The Telemetry and Communication Problem of Re-Entrant Space Vehicles," Proceedings of IRE, Vol. 48, p 703, April 1960.

31. A. A. Dougal, "Experimental Probing of Plasmas With Optical Lasers," Fourth NASA Convention on Plasma Physics, December 1963.

32. W. G. Dow, "Self-Concealment of Plasma Space-Charge Waves," 22nd Convention on Physical Electronics, March 1962.

33. J. E. Drummon, "Basic Microwave Properties of Hot Magnetoplasmas," Physical Review, Vol. 110, No. 2, April 15, 1958.

34. J. Drummond, Plasma Physics, McGraw-Hill Book Company, Inc., New York, 1961.

35. J. Drummond, "Amplification and Evanescent Waves in Plasma," Proceedings of Fifth International Conference on Ionization Phenomena in Gases, Amsterdam, North Holland, 1961.

36. A. L. Eichenbaum and H. Sobol, "Extraction of High-Density Electron Beams From Synthesized Plasmas," 23rd Convention on Physical Electronics, March 1963.

37. W. C. Eppers, "Dark Space Temperature and Ion Velocity in the Cold Cathode Glow Discharge," 22nd Convention on Physical Electronics, March 1962.

38. Ya B. Faynberg, "Interaction of Beams of Charged Particles With Plasma," AD 605901, Fizika Plazmy I Problemy Upravlyayemogo Termoyadermogo Sintez, Ukrainian AN Kiev, pp 88-117, March 1964.

39. A. M. Fedorchenko, "On the Question of Exciting Longitudinal Waves in Plasma by Radio Waves," AD 608248, Ukrainskiy Fizichniz Zhurnal (Ukrainian), Vol. 8, No. 5, p 555, 1963.

40. J. A. Fejer, "Interaction of an Antenna With a Hot Plasma and the Theory of Resonance Probes," NBS Report, Vol. 68D, No. 11, p 1171, November 1964.

41. A. M. Ferendeci, "Guided Waves in an Anisotropic Plasma," Fourth NASA Convention on Plasma Physics, December 1963.

42. R. L. Ferrari, "An Electron Beam-Plasma Amplifier at Microwave Frequencies," Journal of Electronics and Control, Vol. 17, No. 1, p 49, July 1964.

43. David Finkelstein, "Dynamics of Plasmas," Physics Today, Vol. 15, No. 12, p 43, December 1962.

44. D. Gabor, E. A. Ash, and D. Dracott, "Langmuir's Paradox," Nature, Vol. 176, No. 4487, p 916, November 12, 1955.

45. S. Gasionowicz, M. Newman, and R. J. Riddell, "Dynamics of Ionized Media," Physical Review, Vol. 101, No. 3, p 922, February 1, 1956.

46. Ward D. Getty, "Investigation of Electron-Beam Interaction With a Beam-Generated Plasma," Technical Report 407, Massachusetts Institute of Technology, Research Laboratory of Electronics, Cambridge, Massachusetts, January 19, 1963.

47. A. L. Gilardini and S. C. Brown, "Microwave Conductivity for Ionized Decoying Plasma at Low Pressures," Physical Review, Vol. 105, No. 1, p 25, January 1, 1957.

48. K. A. Graf and M. P. Bachynski, "Existing Solutions for Interaction of Electromagnetic Waves With Plasma of Simple Geometries," AD 277201, RCA Victor Company, Ltd., Research Laboratories, Montreal, Canada, June 1962.

49. K. A. Graf and M. P. Bachynski, "Transmission and Reflection of Arbitrarily Polarized Electromagnetic Waves at the Boundary of an Anisotropic Plasma," AD 276362, RCA Victor Research Report 7-801, 14, Contract No. AF19(604)-7432, Radio Corporation of America, January 1962.

50. H. A. Haus and D. L. Bobroff, "Small Signal Power Theorem for Electron Beams," Journal of Applied Physics, Vol. 28, No. 6, pp 694-704, June 1957.

51. P. Hedvall, "Properties of a Plasma Created by an Electron Beam," Journal of Applied Physics, Vol. 33, No. 8, p 2426, August 1962.

52. B. D. Henshall, "Revised Program Plan for the Plasma Research Project of the Advanced Re-Entry Systems Program," AD 452871, Nr-21-R138.1, Avco Corporation, Wilmington, Massachusetts, May 1962.

53. H. Hodara, "The Use of Magnetic Fields in the Elimination of Re-Entry Blackout," Proceedings of IRE, Vol. 49, p 1825, December 1961.

54. H. Hodara and G. I. Cohn, "Highlights of Laboratories Division Research Program," AD 459904, Report No. ATN-63(9990)LH-7, Aerospace Corporation, El Segundo, California, July 1963.

55. H. Hodara and G. I. Cohn, "Radiation Characteristics of Long Narrow Slot Antennas in Lossy Anisotropic Plasmas," National Electronics Conference Proceedings, Vol. 17, p 622, October 1961.

56. J. E. Hopson, "Beam-Generated Beam-Plasma System," Journal of Applied Physics, Vol. 34, No. 8, p 2425, August 1963.

57. James E. Hopson, "Electromagnetic Wave Propagation in Gyro-Electric Plasmas," Report No. NA 8210-8191-2, Contract No. AF19(604)-5555, Electronic Tube Division, Sperry Gyroscope Corporation, Great Neck, New York, April 1960.

58. James E. Hopson, "Hollow Cathode Beam-Plasma Transmission Study," Martin Report No. 13182P, The Martin Company, Baltimore, Maryland, October 1963.

59. R. C. Hwa, "Effects of Electron-Electron Interactions on Cyclotron Resonances in Gaseous Plasmas," Physical Review, Vol. 110, No. 2, p 307, April 15, 1958.

60. J. R. Jedlicka, "Measurement of Stream Velocity With Faraday Probes," Fourth NASA Convention on Plasma Physics, December 1963.

61. T. W. Johnston, "Modulated Electron Beam Diagnostics in Plasmas," AD 274266, Final Report, Contract No. AF19(604)-7246, Radio Corporation of America, January 1962.

62. M. Katzin, A. D. Parsons, and D. L. Ringwalt, "RF Impedance Probe for Reentry Plasma Sheath Measurements," AD-430,999, Report BSD-299-4, Electromagnetic Research Corporation, College Park, Maryland, December 13, 1963.

63. A. J. Kelly, "A Microwave Probe for Plasma Plumes," Technical Report No. 32-625, Jet Propulsion Laboratory, November 1, 1965.

64. G. Kino, Electrodynamics and Fluid Dynamics of Gaseous Plasma, Polytechnic Press of the Polytechnic Institute of Brooklyn, New York, Vol. XI, 1962.

65. M. J. Kofoid, "Experimental Two-Beam Excitation of Electron Oscillation in a Plasma," 13th Annual Gaseous Electronic Conference, 1960.

66. M. J. Kofoid, "Experimental Two-Beam Excitation of Electron Oscillation in a Plasma Without Sheaths," Physical Review Letters, Vol. 4, No. 10, p 541, May 15, 1960.

67. M. A. Kovner, "Instability of Low-Frequency Electromagnetic Waves in a Plasma Traversed by a Beam of Changed Particles," Soviet Physics JETP, Vol. 13, No. 2, p 369, August 1961.

68. J. D. Lawson, "On the Adiabatic Self-Constriction of an Accelerated Electron Beam Neutralized by Positive Ions," Atomic Energy Research Establishment, Harwell, Berks, October 13, 1957.

69. H. G. Lew and V. A. Langelo, "Plasma Sheath Characteristics About Hypersonic Vehicles," Contract No. AF04(647)-269, Space Sciences Laboratory, General Electric Company, Philadelphia, Pennsylvania, April 1960.

70. E. G. Linder and K. G. Hernquist, "Space-Charge Effects in Electron Beams and Their Reduction by Positive Ion Trappery," Journal of Applied Physics, Vol. 21, No. 11, p 1088, November 1950.

71. J. Litton, "Electron Beam Mode Discharge Studies," Fourth NASA Convention on Plasma Physics, December 1963.

72. J. Litton and H. L. L. Van Paassen, "Electron Beam Production From Perforated Wall Hollow Cathode Discharges," 23rd Convention on Physical Electronics, March 1963.

73. James Litton, "Hollow Cathode Beam-Plasma Interaction Study," Martin Report No. ER 12833P, The Martin Company, Baltimore, Maryland, January 1963.

74. James Litton, "Hollow Cathode Beam as an Active Radiator for Electromagnetic Energy," Martin Report No. ER 13105, The Martin Company, Baltimore, Maryland, August 1963.

75. Duncan H. Looney and Sanborn C. Brown, "The Excitation of Plasma Oscillations," Physical Review, Vol. 93, No. 5, p 965, March 1, 1954.

76. M. S. Macrakis, "Incoherent Scattering From a Plasma," Technical Report No. 287, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Massachusetts, November 1962.

77. N. Marcuvitz, "Propagation of Waves in Plasma," Physics Today, Vol. 15, No. 12, p 38, December 1962.

78. B. V. Markevitch and F. C. Hurlbut, "The Study of Electron Beam Attenuation in Air," University of California, Institute of Engineering Research, Berkeley, California, Series No. 20, Issue No. 112, February 9, 1957.

79. T. R. Mc Pherron, P. J. Anderson, and A. F. Ruehl, "Study and Experimentation on Modulation Degradation by Ionized Flow Fields," Technical Report AFAL-TR-65-46, McDonnell Aircraft Corporation, February 1965.

80. W. E. Meador, "Reentry Heat Transfer and Plasma Statistics," Fourth NASA Convention on Plasma Physics, December 1963.

81. G. Medicus, "Theory of Electron Collection of Spherical Probes," Journal of Applied Physics, Vol. 32, No. 11, p 2512, November 1, 1961.

82. G. Medicus, "Spherical Probes With Pre-Sheath," 22nd Convention on Physical Electronics, March 1962.

83. D. B. Medved, "On the Formation of Electron Sheath Around Satellites," 21st Annual Convention on Physical Electronics, March 1961.

84. G. Meltz and R. A. Shore, "Leaky Waves Supported by Uniaxial Plasma Layers," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 1, p 94, January 1965.

85. G. Meltz and H. J. Schmitt, "Observations of the Effect of Magnetic Fields on the Radiation From Plasma-Covered Antennas," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 1, p 169, January 1965.

86. J. Menkes, "Scattering of Radar Waves by an Underdense Turbulent Plasma," AIAA Aerospace Science Meeting, New York, New York, January 1964.

87. E. Muly, "Hollow Cathode Beam Plasma Interaction Study," Final Report, Martin Report ER 13401, Contract No. NASw-714, The Martin Company, Baltimore, Maryland, January 1964.

88. E. Muly, "Hollow Cathode Beam Plasma Interaction Study," First Quarterly Report, Contract No. NASw-714, The Martin Company, Baltimore, Maryland, September 1963.

89. E. C. Muly, "Electron Emission From Screen Mesh Cathode Surfaces," 24th Convention on Physical Electronics, March 1964.

90. A. Olte, M. L. Barasch, E. G. Fontheim, A. E. Heins, J. S. King, and E. K. Miller, "An Investigation of the Absorption of Electromagnetic Radiation by a Plasma of Sub-Critical Density," AD 274014, Final Report, The University of Michigan, College of Engineering, Department of Electrical Engineering, Radiation Laboratory, February 1962.

91. L. Oster, "Interaction of Radiation and Matter in a Plasma," ARL 64-202, Office of Aerospace Research, United States Air Force, November 1964.

92. P. Parzen, "Scattering of an Electron Beam by a Neutral Gas," Journal of Applied Physics, Vol. 33, No. 6, p 2062, June 1962.

93. N. E. Pedersen and J. Davis, "Electromagnetic Absorption Effects in Plasma Spheres," RAD-TR-64-37, Avco Corporation, Wilmington, Massachusetts, November 25, 1964.

94. H. E. Petschek, "High-Temperature Plasmas," Physics Today, Vol. 15, No. 12, p 50, December 1962.

95. David Pines, "Plasma Oscillation of Electron Gases," Proceedings of the International Congress of Many-Particle Problems, June 1960.

96. V. J. Rossow, "An RF Probe System to Measure the Conductivity and Velocity of Plasmas," Fourth NASA Convention on Plasma Physics, December 1963.

97. P. D. Rowley, "The Absorption of Vertically Polarized Plane Electromagnetic Waves in Thin Slabs of Plasma," Fourth NASA Convention on Plasma Physics, December 1963.

98. P. E. Serafim, "Analysis of Electron Beam-Plasma Systems," AD 609023, Report No. 423, Massachusetts Institute of Technology, Research Laboratory, Cambridge, Massachusetts, July 31, 1964.

99. S. R. Seshadri, "Radiation From Electromagnetic Sources in a Plasma," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 1, p 79, January 1965.

100. S. R. Seshadri, "Radiation Propagating Transverse to the External Magnetic Field From an Electromagnetic Source in an Unbounded Plasma," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 1, p 106, January 1965.

101. J. C. Slattery and R. F. Kemp, "Plasma Potential Probe Using Electron Time-of-Flight," The Review of Scientific Instruments, Vol. 33, No. 4, p 463, April 1962.

102. M. R. Smith and W. B. Johnson, "Rates of Energy Loss of Energetic Electrons in a Plasma," Parts I and II, Fourth NASA Convention on Plasma Physics, December 1963.

103. L. D. Smullin and W. D. Getty, "Generation of a Hot, Dense Plasma by a Collective Beam-Plasma Interaction," Physical Review Letters, Vol. 9, No. 1, p 3, July 1, 1962.

104. Robert P. Stein, "Electrical Fields in the Crookes Dark Space of a Low Pressure Glow Discharge in Air and N_2," Physical Review, Vol. 89, No. 1, p 134, January 1, 1953.

105. T. H. Stix, "Oscillations of a Cylindrical Plasma," Physical Review, Vol. 106, No. 6, p 1146, June 15, 1957.

106. H. Suhl and L. R. Walker, "Topics in Guided-Wave Propagation Through Gyromagnetic Media, Part I: The Completely Filled Cylindrical Guide," The Bell System Technical Journal, Vol, 33, No. 3, p 579, May 1954.

107. R. Targ and L. P. Levine, "Backward-Wave Microwave Oscillations in a System Composed of an Electron Beam and a Hydrogen Gas Plasma," Journal of Applied Physics, Vol. 32, No. 4, p 731, April 1961.

108. L. S. Taylor, "RF Reflectance of Plasma Sheaths," Proceedings of IRE, Vol. 49, p 1831, December 1961.

109. L. S. Taylor, "Scattering of Radio Waves by Dense Turbulent Plasmas," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 1, p 122, January 1965.

110. F. J. Tischer, "Communication Blackout at Reentry," Proceedings of the Fifth International Symposium on Space Technology and Science, Tokyo, Japan, September 2-7, 1963.

111. K. J. Touryan, "The Hypersonic Plasma Converter II," SC-RR-64-979, AD 608684, Sandia Laboratory, Albuquerque, New Mexico, November 1964.

112. A. W. Trivelpiece and R. W. Gould, "Space Charge Waves in Cylindrical Plasma Columns," Journal of Applied Physics, Vol. 30, No. 11, p 1784, November 1959.

113. N. S. Tuan and S. R. Seshadri, "Radiation From a Uniformly Moving Distribution of Electric Charge in an Anisotropic, Compressible Plasma," IEEE Transactions on Antennas and Propagation, Vol. AP-13, No. 1, p 71, January 1965.

114. G. E. Vibrans, "Field Emission in Vacuum Voltage Breakdown," Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Massachusetts, Technical Report 353, May 8, 1964.

115. M. T. Vlaardingerbroek, "Excitation of Ion Oscillations in Beam-Plasma Systems," Technical Report 426, Massachusetts Institute of Technology, Research Laboratory of Electronics, Cambridge, Massachusetts, September 18, 1964.

116. H. W. Wassink and A. J. Estin, "Investigation of Plasma Boundaries With Electromagnetic Surface Waves," Journal of Applied Physics, Vol. 35, No. 10, p 2975, October 1964.

'117. G. Wehner, "Electron Plasma Oscillation," Journal of Applied Physics, Vol. 22, No. 6, p 761, June 1951.

118. R. F. Whitmer and A. D. MacDonald, "RF Antenna Breakdown Conditions in the Presence of the Plasma Sheath," Planetary and Space Science, Vol. 6, June 1961.

119. Ching-Sheng Wu, "High-Frequency Conductivity of a Plasma in Quasi-Equilibrium. II. Effect of a Uniform Magnetic Field," Technical Report No. 32-821, Jet Propulsion Laboratory, November 30, 1965.

120. S. V. Yadavalli, "Distortion of Signals Propagating Through a Plasma," Proceedings of IEEE, Vol. 51, No. 6, p 956, June 1963.

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