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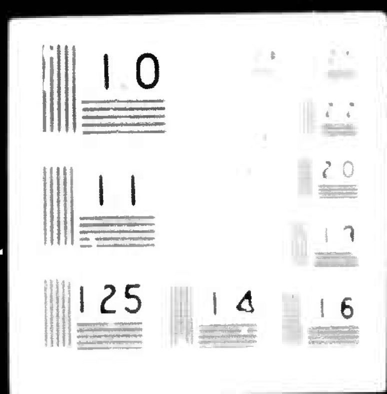

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SU-IPR Report No. 201

TECHNICAL REPORT ECOM-02040-10

Investigation of Fast Wave Beam-Plasma Interactions

Quarterly Report No. 6

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CONTRACT DA 28-043 AMC-02040(E)

INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

INVESTIGATION OF FAST WAVE
BEAM/PLASMA INTERACTIONS

U. S. Army Electronics Command
Fort Monmouth, New Jersey

REPORT NO.10

CONTRACT DA-28-043-AMC 02041(E)

6TH QUARTERLY REPORT
1 June - 31 August 1967

SU-IPR Report No. 201
September 1967

Institute for Plasma Research
Stanford University
Stanford, California

PERSONNEL

Contract DA-28-043-AMC-02041(E)

for the period

1 June - 31 August, 1967.

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ABSTRACT

This report describes a program of work on beam/plasma interaction. Both electrostatic and electromagnetic wave amplifying mechanisms are under investigation. For the former, studies in the absence of a static magnetic field are directed towards verifying the theory for the cases of finite beam/infinite plasma, and beam/surface wave amplification, when transverse modulation is applied. Two distinctly different lines are being followed for interactions in the presence of a static magnetic field: Electrostatic cyclotron harmonic wave interaction is being examined, both theoretically and experimentally, and the potentialities of electromagnetic wave growth in the "whistler" mode are being investigated.

FOREWORD

This contract represents a three-year program of research on "Fast Wave Beam/plasma Interactions" which is proceeding in the Institute for Plasma Research, Stanford University, under the direction of Prof. F. W. Crawford as Principal Investigator. The work is part of PROJECT DEFENDER and was made possible by the support of the Advanced Research Projects Agency under Order No. 695. It is conducted under the technical guidance of the U. S. Army Electronics Command. This is the sixth Quarterly Report, and covers the period 1 June to 31 August, 1967.

CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The wave amplification effect associated with the interaction of an electron beam and a plasma has attracted considerable attention over the last few years, particularly from microwave tube specialists to whom such interactions offer possibilities of constructing very high gain devices which should be electronically tunable over wide frequency ranges. Since the plasma plays the role of a conventional slow-wave structure, the interaction region should be free of metallic structures, a particularly significant characteristic if millimeter wave operation is envisaged.

The work being carried out under this contract is directed towards utilizing the beam/plasma amplification mechanism in microwave device applications. So far, despite the efforts of many groups, it has not been found possible to realize this potential fully. The most serious obstacles to progress are that efficient coupling of an rf signal into and out of the interaction region has been found difficult to achieve, and that the amplifiers are frequently very noisy compared with most conventional microwave tubes. The necessity of providing the means of plasma generation within the device, and the presence of a relatively high background gas pressure, add constructional problems beyond those normally encountered with vacuum tubes. Although satisfactory engineering solutions to these latter difficulties could certainly be found, the coupling and noise problems still require considerable further study to determine whether competitive devices can be developed.

Of the many widely differing aspects of beam/plasma interaction, three have been chosen for close examination under this contract. The first of these is the interaction of an electron beam with a plasma when the modulating fields, and the wave growth, are in either the first axisymmetric mode, or in the first azimuthally-varying mode. Since with transverse modulation several interesting interaction and coupling mechanisms become possible, it is intended that a thorough investigation of such phenomena should be made under this contract.

Most previous work has been concerned with the theoretical description and demonstration of beam/plasma interaction mechanisms that can be derived from cold plasma theory, i.e., from theory in which it is assumed that the plasma electrons have no thermal or directed motions, and that the injected beam is monoenergetic. When a dc magnetic field is present, microscopic theory, in which single-particle behavior is followed, predicts a much wider range of amplification mechanisms. Some of these are simply modifications of those occurring in the absence of the magnetic field, while others involve interaction of beams with transverse energy with slow "cyclotron harmonic waves." This constitutes our second area of interest, i.e., that of wave growth in magnetoplasmas when the electron beam has a substantial component of transverse energy.

Our third area of interest is in electromagnetic wave amplification. Theoretical studies show that, in addition to electrostatic wave growth phenomena such as those just described, there is the possibility of obtaining appreciable growth in the "whistler" mode when an electron beam with transverse energy interacts with a magnetoplasma. This mode is a right-hand, circularly-polarized electromagnetic wave, i.e., its electric field vector rotates in the right-hand sense, which is also (conventionally) the sense of rotation of the electrons about the magnetic field lines. If a beam with transverse energy is moving along the field lines, there is consequently a possibility of energy being transferred from the electrons to the wave, and hence, for wave amplification to occur. The purpose of our work is to demonstrate this type of interaction, and to examine its potentiality for coupling to slow- and fast-wave circuits. Here "fast-wave" is interpreted to mean that the phase velocity of the wave is of the order of the velocity of light.

Previous quarterly reports (QR) have described the background for each of the topics in detail. Progress made during the reporting period will be described in the succeeding sections.

II. BEAM/PLASMA AMPLIFICATION

Amplification due to interaction of an electron beam with an unmagnetized plasma has been studied hitherto at Stanford and elsewhere. Experimentally, electronic gains as high as 20 dB/cm, at frequencies up to 1 GHz, have been observed in both $m = 0$ and $m = 1$ modes, and reasonable agreement has been obtained with theoretical predictions. Although electronic gain has been observed, however, the achievement of net gain between an input and an output appears to be an elusive goal due to the difficulty of achieving efficient coupling between the beam/plasma system and external circuits. One of the principal aims of this study is to investigate coupling methods in the hope of realizing net gain.

Consider a system consisting of a beam of radius a interacting with a plasma of radius b $(b \geq a)$. In practice, the plasma will be confined in a dielectric tube which may itself be surrounded at some larger radius by a conducting waveguide. For the present purposes, the specification of the system outside the plasma radius, b, is unimportant. The usual quasistatic analysis of this system exhibits a peculiar ambiguity [1,2] in that it apparently admits of two distinct mode types which have been called the solenoidal and nonsolenoidal modes. This question has been examined in detail in the past quarter and, as is reported in Section A below, it is concluded that the nonsolenoidal mode is fictitious. It arises purely as a result of the approximations made in the usual analysis.

This result justifies the hitherto tacit assumption that it is the solenoidal mode of quasistatic theory that gives the correct description of the interaction for nonrelativistic beams. In this mode, there is no time-varying space-charge within the volume, but there is effectively a surface charge due to rippling of the beam surface. This surface charge acts as a source for the electric fields and for frequencies less than the plasma frequency, when growth occurs, the fields are concentrated near the beam surface.

When b is appreciably greater than a (say $(b/a) > 1.5$), then the field at the radius b is very small, and the coupling to external regions is very weak. Under these conditions the interaction is similar to that for an unbounded (infinite) plasma and is effectively due to coupling between the beam modes and plasma oscillations. For this case, to achieve efficient coupling it would be necessary to introduce coupling circuits either into or close to the beam, i.e. within the plasma, and this raises a variety of difficult practical problems. One possible means of overcoming this difficulty in the case of the $m = 1$ mode was suggested in QR 3, through the use of a locally enhanced plasma density in the coupling regions, such that these regions are resonant in the dipole mode (at $\omega_p/2^{1/2}$) for a frequency close to the local plasma frequency in the main interaction region. Experimentally, however, it proved difficult to achieve the necessary control over the plasma density profile along the axis.

When, however, the beam fills, or nearly fills, the plasma region, ($(b/a) \approx 1$), the fields penetrate appreciably into the region external to the plasma. Under these conditions, provided the plasma is bounded by a dielectric (with or without an additional external conductor), then the interaction is effectively between the space-charge waves of the beam and the surface waves of propagation on the plasma column. In this case, it should be possible to couple efficiently to circuits external to the plasma. This is highly desirable from the practical point of view. For this reason we are studying, both theoretically and experimentally, as reported in Sections B and C below, a system in which the beam and plasma fill a dielectric tube.

(A) Theoretical Studies of Beam/Plasma Interaction.

Solenoidal and Nonsolenoidal Modes: In the usual quasistatic theory of interaction between a cold electron beam of finite radius and a cold, uniform, unmagnetized plasma of the same or greater radius, it appears[1,2] that there are two distinct uncoupled solutions which have been called the solenoidal and nonsolenoidal modes. They have the following characteristics:

(i) Solenoidal Mode - This mode is characterized by having zero time-varying volume space charge so that the electric field has zero divergence, i.e. it is solenoidal. However, there is a surface charge on the beam surface. This acts as a source for the electric fields, which are non-zero both within and outside the beam. The dispersion relation comes from solving the eigenvalue problem when the fields inside and outside the beam are matched, and its form depends on the particular configuration as regards the external boundary of the plasma. For the simple case of an unbounded plasma, the dispersion relation may be written,

$$1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_b^2}{(\omega - \beta v_b)^2} F_1 = 0 \ , \qquad (1)$$

where the space-charge reduction factor $F_1 = \beta a \, I_m'(\beta a) K_m(\beta a)$; m is the azimuthal mode number, and I_m and K_m are modified Bessel functions, the prime denoting differentiation with respect to the argument. There is a complete set of normal mode solutions to Eq. (1) with different β's , corresponding to the various radial modes of the system.

(ii) Nonsolenoidal Mode - This is characterized by the fact that there is no electric field external to the beam, and there is a time dependent volume space-charge within the beam, as well as a surface charge. The rf potential, $\emptyset$, within the beam is arbitrary provided $\emptyset(a) = 0$ at the beam surface. The dispersion relation for this mode is

$$1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_b^2}{(\omega - \beta V_b)^2} = 0 \ , \qquad (2)$$

which is the same as that for one-dimensional motion in an infinite beam/plasma system.

The appearance of two distinct modes is disquieting and, in particular, the appearance of the nonsolenoidal mode with a dispersion relation independent of the geometry, and with no fields outside the beam, is suspect. The predictions of the two modes concerning what would be observed in a practical system are quite disparate, and one is led to inquire which mode would be excited and observed in practice. Furthermore, since one requires fields outside the beam in order to facilitate coupling into and from the system, it is particularly important to resolve this issue. In the past, it has been tacitly assumed that the appropriate mode in a finite beam/plasma system is the solenoidal one, and the existence of the nonsolenoidal mode has been neglected.

In the past quarter, we have examined this problem in detail and find that the occurrence of the two mode types is a degeneracy introduced into the analysis through the use of the quasistatic approximation. By making an exact analysis from the full Maxwell equations, including relativistic effects, one finds just a single mode type which, under appropriate approximation, reduces to the solenoidal mode of the quasistatic analysis. It appears that the nonsolenoidal mode of the quasistatic theory is an artefact introduced through making the quasistatic assumption ab initio.

This result is reassuring in that it justifies the neglect of the nonsolenoidal mode. Furthermore, the full analysis gives precise mathematical conditions, in the form of inequalities, under which the quasistatic dispersion relation, Eq. (1), for the solenoidal mode is valid. This equation is very much simpler to solve for $k(\omega)$, or $\omega(k)$, than the full dispersion relation, and one may use it, rather than the latter, provided one checks a posteriori that the exact conditions for its validity are indeed fulfilled. A full report on this work is in preparation and will be issued shortly.[3]

Surface Wave Interaction: We are concerned here with developing the theory for interaction between an electron beam and a plasma both filling a dielectric tube $(\epsilon = \epsilon_g)$ of radii a , b , surrounded by an air-spaced waveguide of radius c . The quasistatic dispersion relation for this system was given in QR 5 (Eqs. 1 to 5). The numerical analysis of the equations is complicated by the large number of parameters $a, b, c, K = (\epsilon_g/\epsilon_0)$ etc., and the types of solution may change quite markedly with change of the parameters. Much insight may be gained, however, through the use of the mode coupling formalism whereby one considers the interaction as due to coupling between the modes which can exist independently on the beam and plasma. For this reason, we first consider the structure of the surface wave modes for the plasma alone.

(i) <u>Surface Waves for the Plasma Alone:</u> For the three-region system under consideration here, the quasistatic dispersion relation for the plasma alone may be written as

$$1 - \frac{\omega_p^2}{\omega^2} = F_m(\beta,a,b,c,K) \quad , \qquad (3)$$

or

$$\frac{\omega}{\omega_p'} = \left[\frac{1 + K}{1 - F_m}\right]^{1/2} \qquad (3a)$$

where $\omega_p' = \omega_p/(1 + K)^{1/2}$, and $F_m(\beta,a,b,c,K)$ was defined in [illegible] 5. The structure of the dispersion diagram for the various modes, m , depends on K , and on the ratios (b/a) , (c/a) . In practice, the first two quantities are fixed within a certain range by practical consideration, but we are free to vary the relative size of the waveguide. Dispersion diagrams for the first few modes are shown in Fig. 1 for the practical values $K = 4.6$, $(b/a) = 1.18$ and for two values of $(c/a) = 1.90$ and 1.36 . The frequency is normalized to ω_p' and the wavenumber to $(1/a)$. The symmetric mode $m = 0$ propagates down to zero frequency, and is a forward wave at low frequencies, but may become backward at higher frequencies depending on the geometry. The higher order modes only propagate in a certain frequency band, and may be either forward or backward waves.

Some general analytic results, pertaining to the structure of the dispersion diagram, that are relevant to beam/plasma interaction may be obtained as follows:

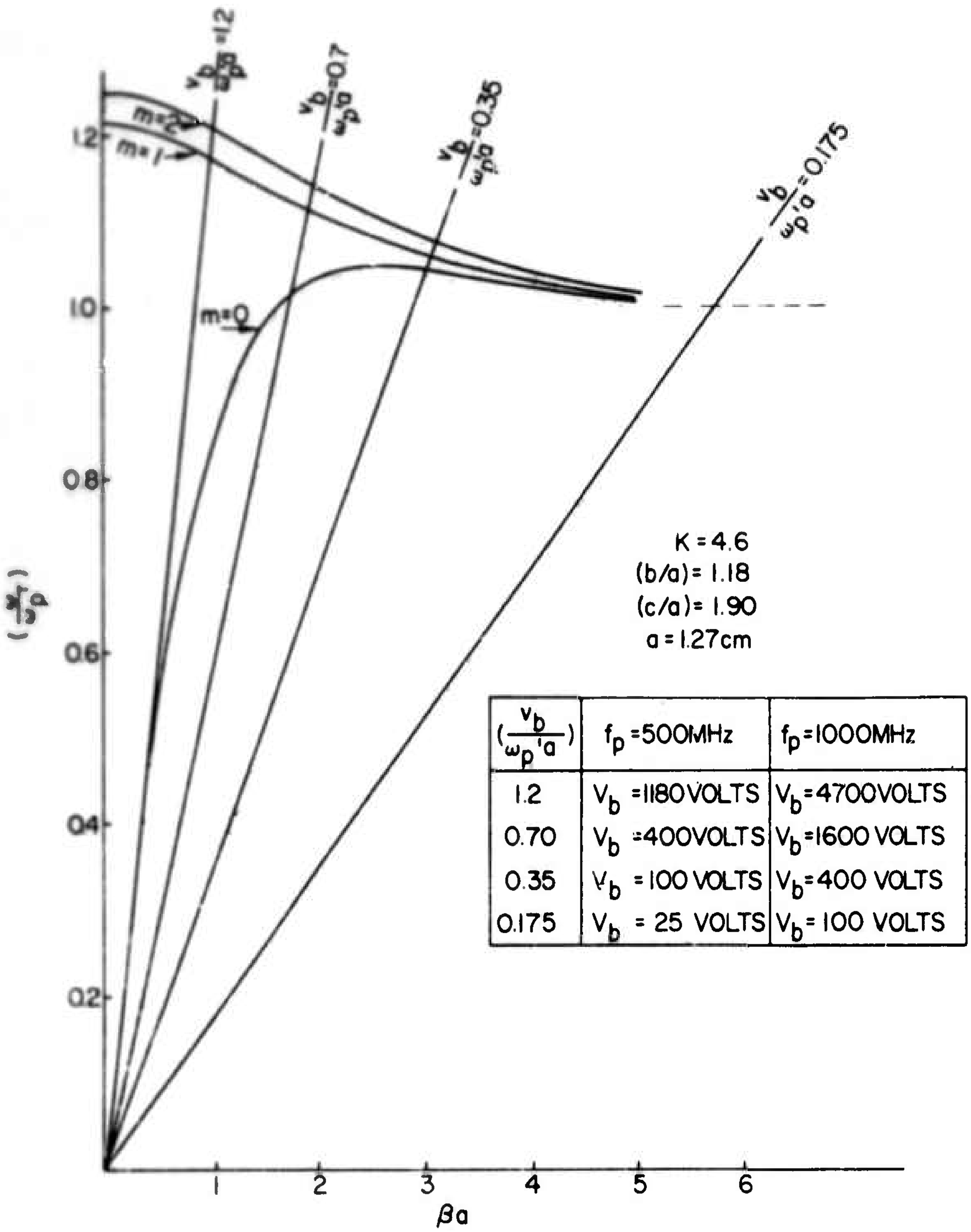
For $\beta \to \infty$, $\omega \to \omega_p'$ for all modes. Thus all modes are asymptotic to $\omega = \omega_p'$, for all values of the parameters.

For $\beta \to 0$, $m = 0$ we have

$$\frac{\omega}{\omega_p'} \to \left[\frac{(1 + K)[K \ln(c/b) + \ln(b/a)]}{2K}\right]^{1/2} (\beta a) \qquad (4)$$

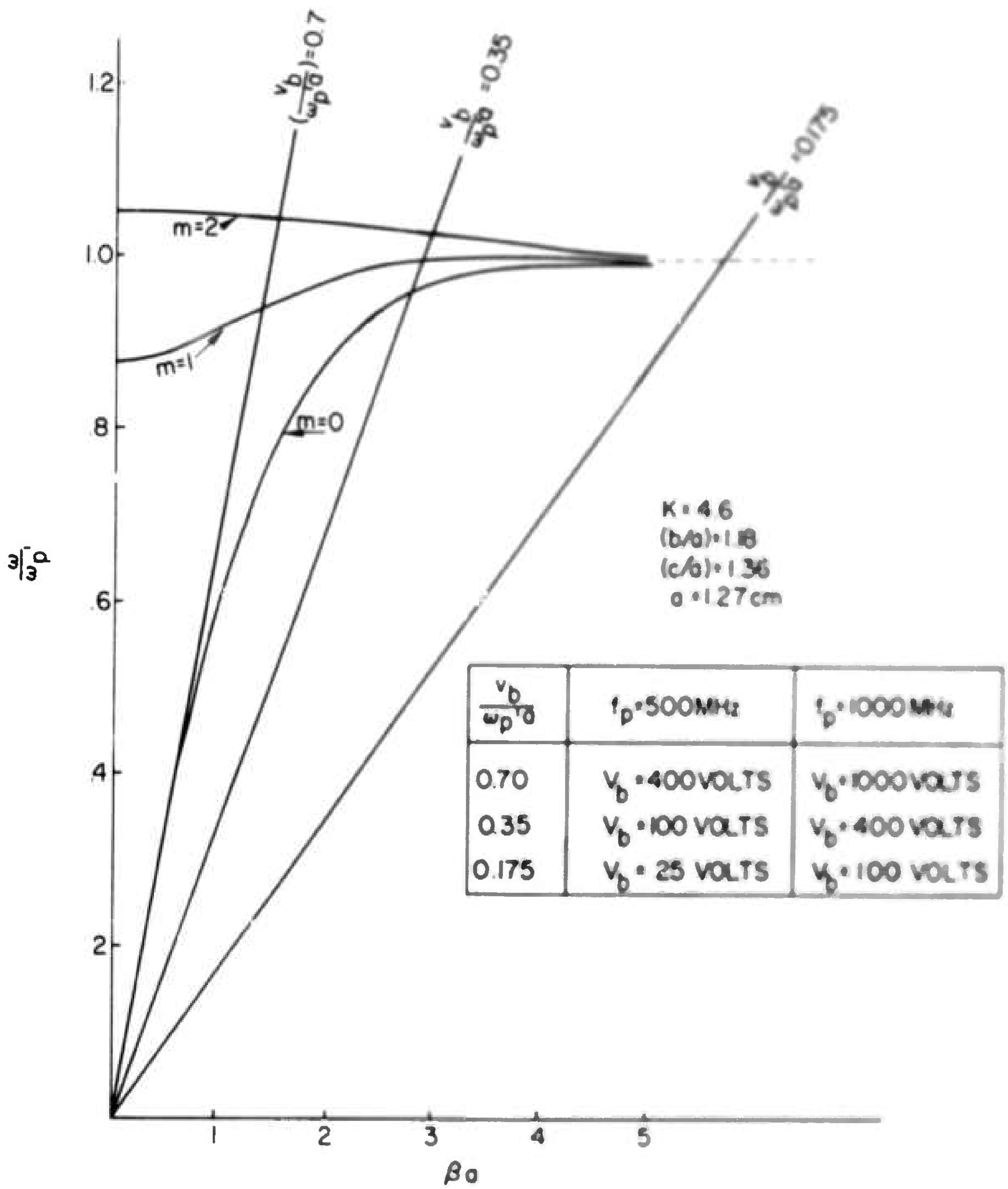
$$\approx \left[\frac{(1 + K) \ln(c/b)}{2}\right]^{1/2} (\beta a) \qquad (4a)$$

when $a \approx b$.



$(\frac{v_b}{\omega_p' a})$	f_p = 500MHz	f_p = 1000MHz
1.2	V_b = 1180 VOLTS	V_b = 4700 VOLTS
0.70	V_b = 400 VOLTS	V_b = 1600 VOLTS
0.35	V_b = 100 VOLTS	V_b = 400 VOLTS
0.175	V_b = 25 VOLTS	V_b = 100 VOLTS

1 (a) **Surface Wave Propagation Characteristics.** (c/a) = 1.90



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0.175	V_b = 25 VOLTS	V_b = 100 VOLTS

1 (b) Surface Wave Propagation Characteristics, (c/a) = 1.36

This gives the initial slope of the $m = 0$ dispersion curve and is important in determining whether interaction with a beam may occur in the $m = 0$ mode, as discussed below. From Eq. (4) we have for the phase velocity near the origin

$$v_{p0} = \frac{\omega}{\beta} = \left[\frac{K \ln(c/b) + \ln(b/a)}{2K}\right]^{1/2} \omega_p a \quad . \tag{4b}$$

Since this result is derived in the quasistatic approximation, it is only correct if $v_p << c$, the velocity of light. In practice, the factor $A = [(K \ln(c/b) + \ln(b/a))/2K]^{1/2}$ is of order unity, so we must have $(\omega_p a) << c$. This means that for a given plasma frequency, the tube circumference must be much less than the corresponding free-space wavelength for the quasistatic result of Eq. (4) to be correct. In practical situations this condition is always likely to be satisfied.

For $\beta = 0$, $m \neq 0$, we have

$$F_m = -K\left\{\frac{K[1-(a/b)^{2m}][1-(b/c)^{2m}] + [1+(a/b)^{2m}][1+(b/c)^{2m}]}{K[1+(a/b)^{2m}][1-(b/c)^{2m}] + [1-(a/b)^{2m}][1+(b/c)^{2m}]}\right\} . \tag{5}$$

From Eqs. (5) and (3a) it is clear that depending on m, K, (a/b) and (c/b), then the $\beta = 0$ cut-offs, ω_{cm}, of the higher order modes may lie above or below the large-β asymptotes $(\omega \to \omega_p')$, giving rise, respectively, to backward or forward waves. For any given K, (a/b) and (c/b), it is clear that as $m \to \infty$, $\omega_{cm} \to \omega_p'$ so that the passband is very narrow for high order modes.

In the case of a thin walled dielectric tube, $a \approx b$, we have

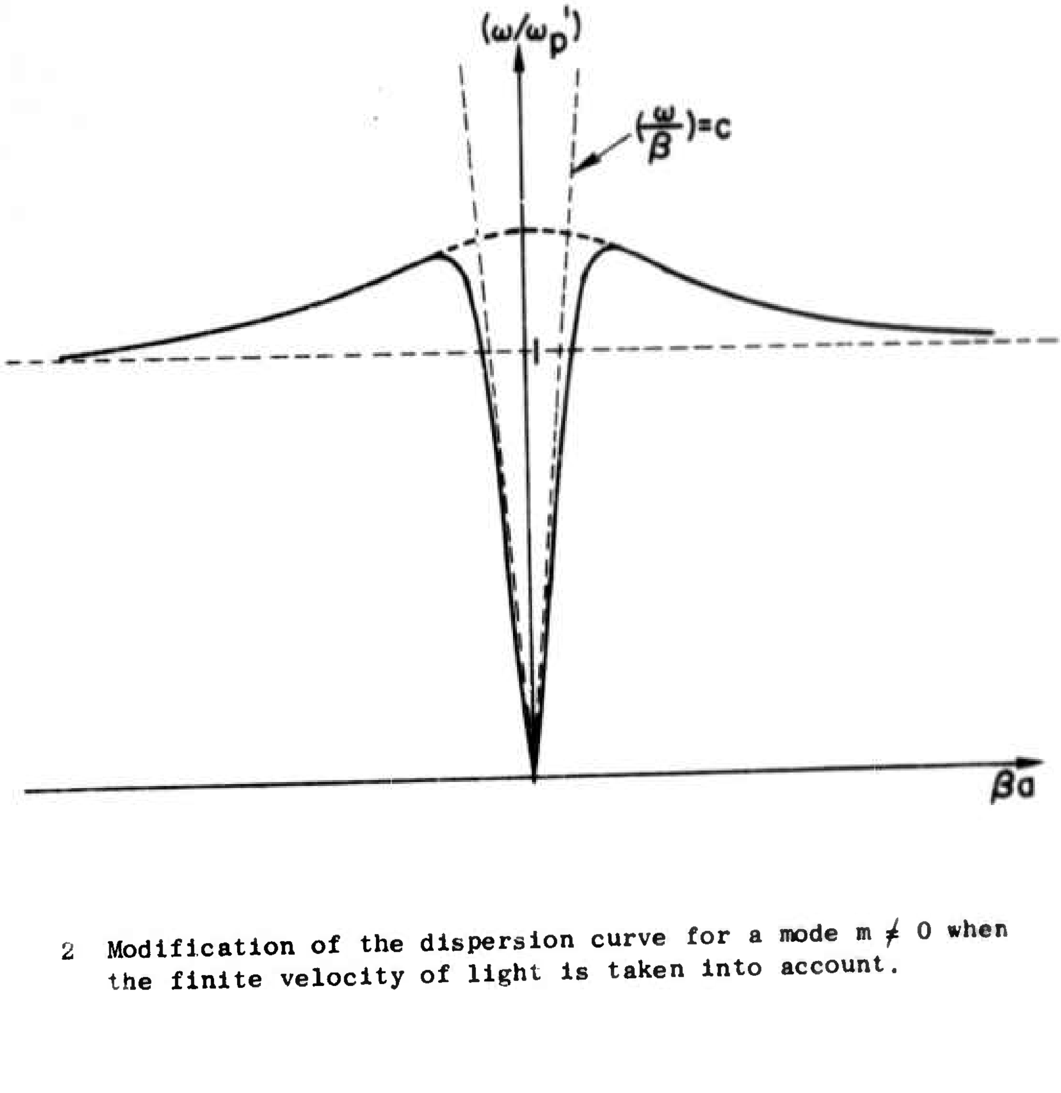
$$\frac{\omega_{cm}}{\omega_{c0}} \approx \left\{ \frac{1 + K}{1 + \frac{[1 + (b/c)^{2m}]}{[1 - (b/c)^{2m}]}} \right\}^{1/2} \quad . \qquad (6)$$

From this it is clear that if $(c/b) > [(K + 1)/(K - 1)]^{1/2}$, the cut-offs ω_{cm} for all modes are greater than $\omega_p{}'$, and all the higher modes are backward. As (c/b) is reduced, then first the $m = 1$ mode, and successively, in order, higher modes become forward waves. Thus in Fig. 1(a), for $(c/a) = 1.90$, the $m = 1$ and all higher order modes are backward, whereas in Fig. 1(b), for $(c/a) = 1.36$, the $m = 1$ mode is a forward wave, but higher modes are still backward. It should be mentioned here that the nonzero cut-offs, ω_{cm} , for $\beta = 0$, for the $m \neq 0$ modes, appear only in the quasistatic approximation. If ω tends to a nonzero value as $\beta \to 0$, it is implied that the phase velocity $(\omega/k) \to \infty$, and one must expect the quasistatic approximation to break down as the dispersion curve approaches the light cone $(\omega/k) = c$. This is illustrated in Fig. 2, where it is seen that in an exact analysis for the $m \neq 0$ modes, as $\beta \to 0$, the dispersion curve becomes asymptotic to the light cone and passes through the origin while additional fast electromagnetic waves appear within the light cone.

(ii) Surface Waves for the Beam Alone: For the three-region system under consideration, the dispersion relation for the beam alone may be written

$$1 - \frac{\omega_b^2}{(\omega - \beta v_b)^2} = F_m(\beta,a,b,c,K) \quad . \qquad (7)$$

It is clear that the modes of the beam alone may be obtained from the modes of the plasma alone by replacing ω_p by ω_b , and performing a



2 Modification of the dispersion curve for a mode $m \neq 0$ when the finite velocity of light is taken into account.

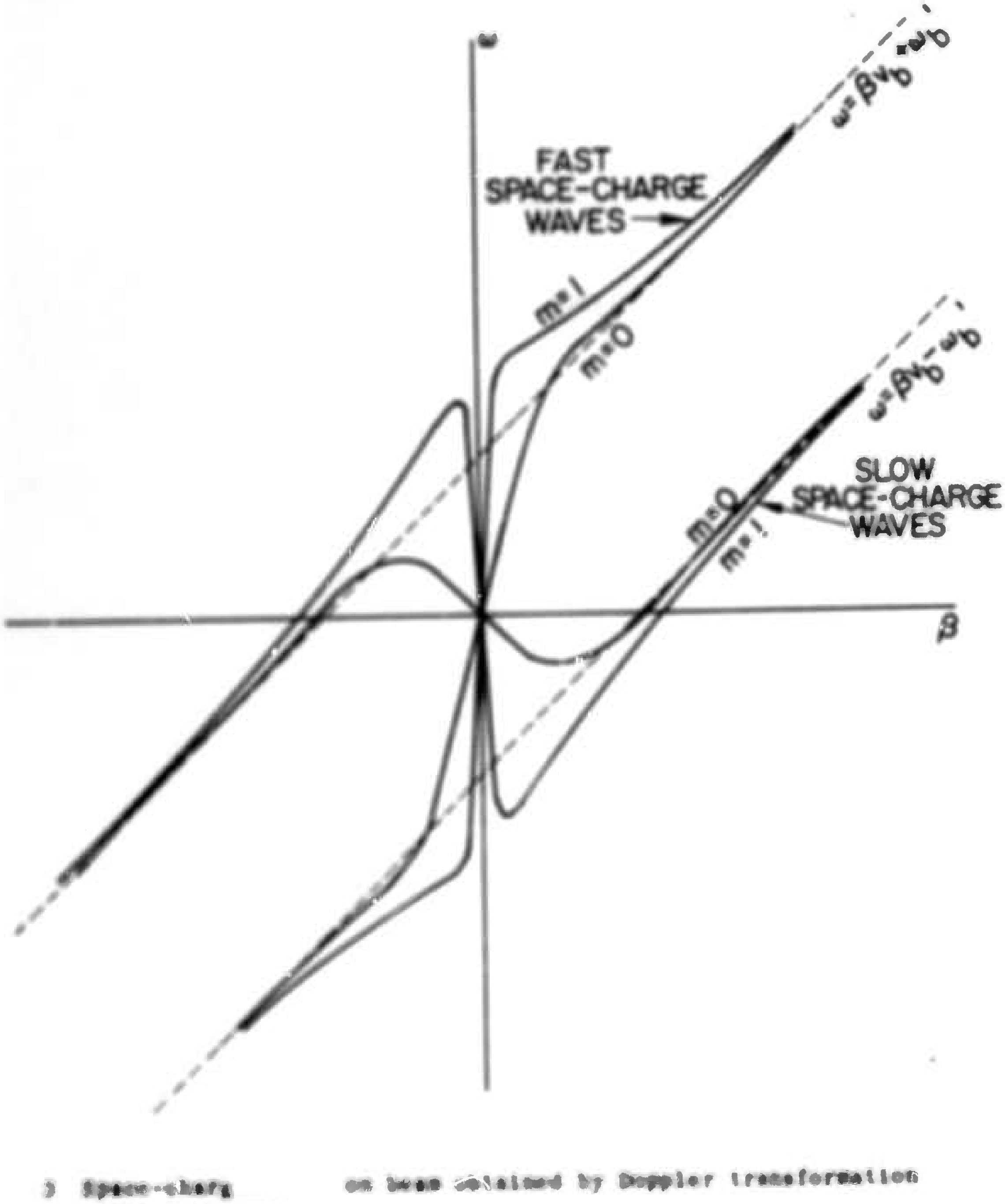
Doppler transformation, $\omega \rightarrow (\omega + \beta v_b)$. This is illustrated for the $n = 0$ and $n = 1$ modes in Fig. 3, corresponding to the parameter values of Fig. 1(a). For each n-value, there are two surface waves on the beam which are asymptotic to $\omega = (\beta v_b \pm \omega_b{}')^{1/2}$. The positive sign corresponds to the fast space-charge wave, while the lower corresponds to the slow space-charge wave.

(iii) Coupling of Plasma and Beam Modes: To investigate the coupling between the plasma and beam modes, it is necessary to superimpose the dispersion diagrams for the beam modes on the diagram of the plasma modes. In order to do this, it is necessary to specify the ratio (ω_b/ω_p) and the quantity $(v_b/\omega_p a)$. The former quantity determines the separation of the two beam waves. The latter determines the slope of the beam waves, and thus whether or not they intersect the $n = 0$ plasma mode.

The ratio $(\omega_b/\omega_p)^2$ is just the ratio of the beam density to the plasma density, and in practical arrangements, including the beam-generated plasma system we are using experimentally, is likely to be appreciably less than unity. Consequently, the separation of the two beam modes will be quite small when represented on a dispersion diagram in which the frequency is normalized to ω_p.

Since the separation of the beam modes is small, they will both lie close to the line $\omega = \beta v_b$, and in order to determine whether the slow space-charge wave of the beam intersects the $n = 0$ plasma mode, under which condition one expects the possibility of growth in the $n = 0$ mode, it is sufficient to compare the slope of the line representing the beam velocity, $(\omega/\beta) = v_b$, with the initial slope, v_{p0}, of the $n = 0$ mode given by Eq.(4b). If $v_b < A\omega_p a$, the intersection occurs and growth in the $n = 0$ mode should occur, whereas if $v_b > A\omega_p a$, there is no intersection, and no growing wave solutions. The coefficient $A \equiv [(K(\ln c/b) + \ln(b/a))/2K]^{1/2}$ depends on the geometry. For the parameters of Figs.1(a) and 1(b) it assumes the values 0.51 and 0.50, respectively.

On Figs. 1(a) and 1(b), a number of beam lines corresponding to different values of $(v_b/\omega_p a)$ are indicated, including the limiting ones that are just tangential to the $n = 0$ mode. The beam voltages



) Space-charg on beam obtained by Doppler transformation
of plasma waves.

corresponding to these lines are shown for two assumed values of the plasma frequency, namely 500 and 1000 MHz, in the inset tables.

For the higher-order modes, $m \geq 1$, it is clear that the beam modes always intersect the plasma modes and interaction will always occur. Two distinct types of interaction are possible according to whether the plasma mode is a forward wave or a backward wave at the point of intersection. In the first case, as for example the $m = 1$ mode in Fig. 1(b), the mode coupling theory leads one to expect a convective instability, that is to say, a wave growing in space in the beam direction, so that one might use it in an amplifier. In the second case, as for example the $m = 1$ mode in Fig. 1(a), mode coupling theory leads one to expect a nonconvective, or absolute instability, so that the system will behave like a backward-wave oscillator. These statements, however, need to be qualified as follows. In the case of a forward-wave interaction, if there is sufficient reflection at the ends of the system and there is a wave which can propagate in the reverse direction, then the system will oscillate if there is some frequency for which the total phase charge around the system is an integral of 2π, and the loop gain is greater than unity. In the case of a backward-wave interaction, the system will only oscillate if it is greater than a critical length. Otherwise it will behave like a backward-wave amplifier with the amplitude of the wave increasing in the direction opposite to the beam.

It should be pointed out that the foregoing ideas concerning the instability types to be expected from an examination of the uncoupled modes are based on the simple theory of the coupling of two modes. This is at best an approximation, and can lead to incorrect conclusions concerning the instability type to be expected. Consequently there is need to carry out a thorough analysis for the particular system under consideration, employing the rigorous criteria [4] for the determination of instability and wave types. This we propose to do in the forthcoming reporting period.

(iv) <u>olutions for the Beam/Plasma System</u>: The waves that can propagate on the combined beam/plasma system are given by solutions of the dispersion relation,

$$1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_b^2}{(\omega - \beta v_b)^2} = F_m(\beta) \quad . \qquad (8)$$

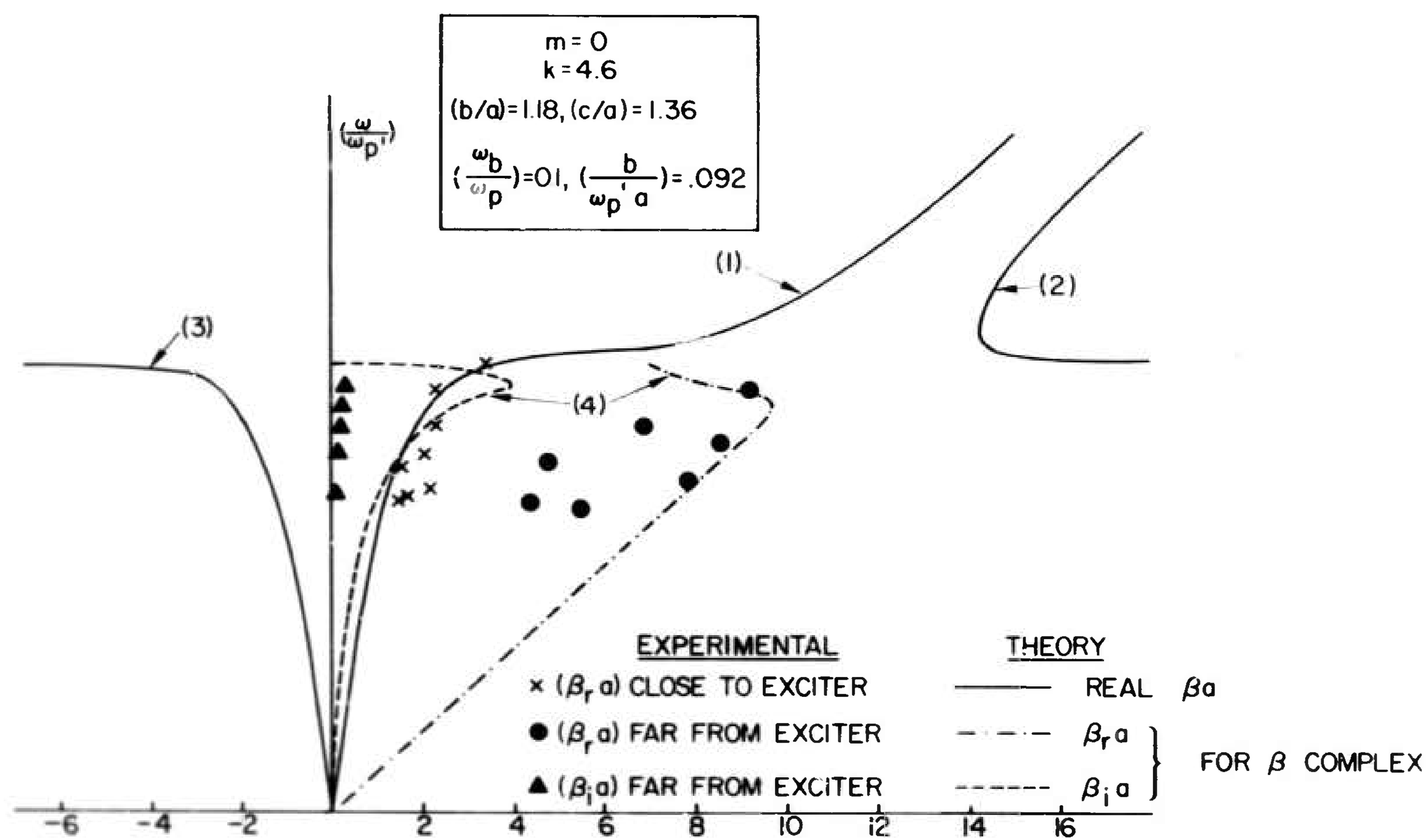
This equation may be regarded as a quartic for $\omega(\beta)$ or as a transcendental equation for $\beta(\omega)$. Because F is real when β is real, one may find the solutions for simple propagating waves, i.e. with ω and β both real, by solving for the real roots of the quartic ω (β real) .

Such solutions for the $m = 0$ mode, for the geometry of Fig. 1(b) and for $(\omega_b/\omega_p)^2 = 0.01$, $(v_b/\omega_p'a) = 0.092$ are shown in Fig. 4 as full lines. These parameter values are chosen to correspond, as well as can be judged, to the experimental values reported below. There are three such simple propagating waves indicated: First, a mode propagating in the positive (beam) direction, which is asymptotic to the plasma mode for $\omega < \omega_p'$ and asymptotic to the fast beam mode for $\omega > \omega_p'$; second, a mode propagating in the positive direction which is asymptotic to the plasma mode near $\omega = \omega_p'$, and asymptotic to the slow beam mode for $\omega > \omega_p'$, and third a reverse mode, i.e. one propagating in the negative direction (opposite to the beam). This is effectively a pure plasma mode since it is almost unaffected by the presence of the beam.

Besides these real-ω, real-β roots, there are, for $\omega < \omega_p'$ an infinite set of complex-β roots for real ω . The first of this set is also indicated on Fig. 4 as Mode (4). One may interpret this root as corresponding to an amplifying wave, but this interpretation is only tentative since the system may possibly be absolutely unstable, and a full stability analysis is necessary to settle this point. In the next quarter is is planned to examine this question in detail and also to study numerical solutions for the $m = 1$ mode.

(B) <u>Experimental Work on Beam/Plasma Interaction.</u>

<u>The Beam/Plasma Tube</u>: The discharge tube designed for the experimental study of beam/plasma interaction employing surface modes, illustrated in Fig. 3 of QR 4, employs a beam-generated plasma in mercury-vapor. An electron beam of a few hundred volts energy, and a few milliamps current, is formed in a planar triode gun, and passes into the mercury-vapor (pressure ~ 2 mTorr at room temperature). Under these



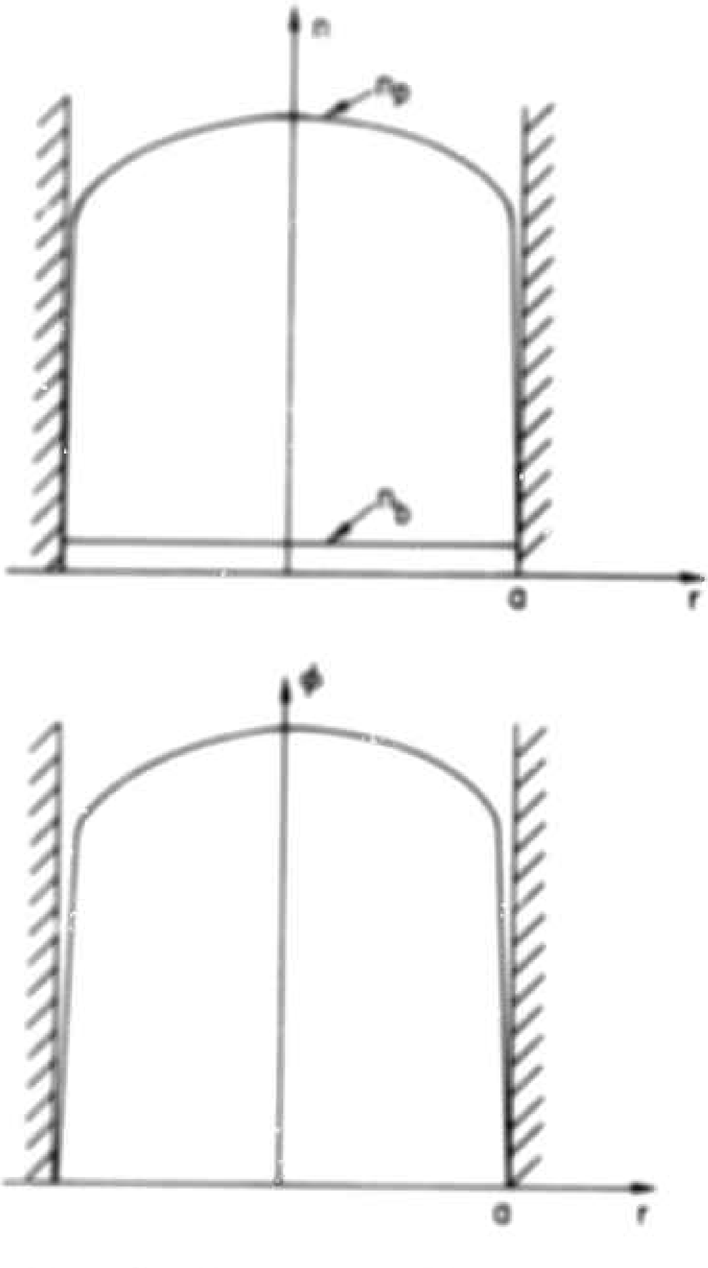
4 Surface wave propagation characteristics for the m = 0 mode: Comparison between experiment and theory.

conditions a steady-state theory[5] shows that the beam may travel the length of the tube with little collisional scattering, yet create by ionization a plasma whose number density, n_p, may be one or two orders of magnitude higher than the number density of the beam, n_b. Previous experience at Stanford with such beam-generated plasmas, in which the beam only partially fills the tube, have confirmed this, and furthermore have shown that such systems may be quiescent provided the growth of spontaneous noise fluctuations due to beam/plasma interaction does not reach large-signal level in the tube length. This offers an advantage over the alternative arrangement, in which a beam is fired into a separately maintained discharge, since the latter is frequently noisy.

Ideally, the electron gun operates much like a vacuum triode in a space-charge limited condition, in which the current is controlled by the first grid. In practice, however, the cathode is more or less temperature-limited. It is then necessary to stabilize the heater power to a high degree and to operate the tube for some considerable time before stable conditions are reached, since the emission is set as a balance between activation and poisoning due to positive ion bombardment.

The steady-state theory of a beam-generated plasma shows that, although the beam density and hence the volume ionization rate are uniform, the plasma density is nonuniform, decreasing with radius as shown in Fig. 5. The plasma density first falls slowly with radius, and then quite rapidly in the sheath region, the latter being of the order of several electronic Debye lengths from the tube wall. Figure 5 also shows the profile of the self-consistent potential, ϕ, which has a similar form to that of the density profile and attains at the wall a value some $(5\ kT_e/e)$ volts below the value on axis, where T_e is the plasma electron temperature $(\sim 1\ \mathrm{eV})$. The nonuniformity in plasma density is important in that it will reduce the growth rate markedly below the values calculated on the basis of a uniform plasma. This point is discussed further below.

<u>Measurements of Wave-propagation</u>: To study wave propagation on the beam/plasma tube, it is mounted coaxially inside a circular waveguide fitted with input and ouput couplers. The couplers are split rings

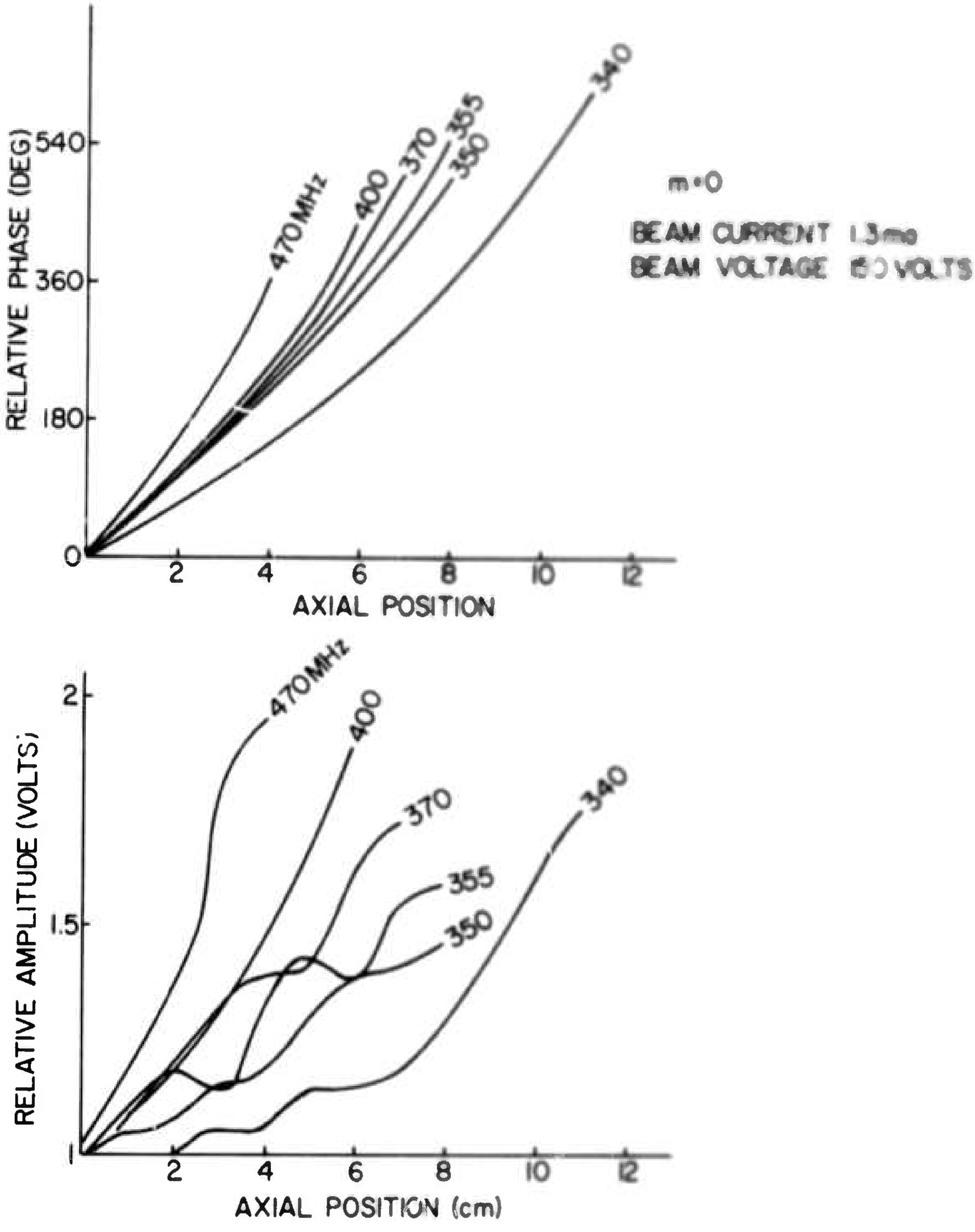


3 Profiles of plasma density, n_p, and self-consistent potential, ϕ, as a function of radius.

touching the glass tube, and may be used to excite and detect either the symmetric $(m = 0)$ or dipole $(m = 1)$ modes, through the use of suitable phase-shifts in the connecting lines. The detecting coupler may be moved along the tube to allow measurements of phase and amplitude to be made as a function of position.

In early experiments, the diameter of the surrounding waveguide was relatively large $((c/a) = 1.90)$, the corresponding plasma mode dispersion diagram being Fig. 1(a). Subsequently, the guide was reduced in diameter to make $(c/a) = 1.36$, the corresponding plasma mode dispersion diagram being Fig. 1(b). This was done in an attempt to avoid interaction in the $m = 0$ mode, so that interaction in the $m = 1$ mode might be more easily observed. However, it appears that even with the smaller guide diameter, because of a limitation of the beam voltage to less than about 300 volts due to the onset of arcing in the gun, it is not possible to avoid the possibility of interaction in the $m = 0$ mode for plasma frequencies in the interesting range of $500 \sim 1000$ MHz. In order to avoid $m = 0$ interaction with low beam voltages and high plasma frequencies, it would be necessary to reduce the discharge tube diameter a. An incidental effect of reducing the ratio (c/a) is also to convert the $m = 1$ plasma mode from a backward wave into a forward wave, as is clear from Figs. 1(a) and 1(b).

Since, for the experimental conditions attainable with the existing tube, interaction in the $m = 0$ mode cannot be avoided, it was decided to take measurements for both the $m = 0$ and $m = 1$ modes, starting with the symmetric mode. Some preliminary measurements of the $m = 0$ mode were reported in QR 5. Further measurements have been made in the past quarter. Figure 6 shows the phase and amplitude of the $m = 0$ wave as a function of position along the tube, as the detecting coupler is moved away from the exciting coupler, for a range of frequencies between 340 and 470 MHz. While the amplitude increases with distance, indicating growth, there is a pronounced interference effect due to a beating of waves with different propagation constants. This effect has been studied and a satisfactory explanation has been developed as follows. Referring to Fig. 4, it is clear that for frequencies $\omega < \omega_p'$, there are two



6 Beam-surface wave interaction: Variation of phase and amplitude along the tube.

waves that can propagate with positive β , i.e. in the beam direction. The first wave, labelled (1), is a simple propagating wave, though, of course, with collisions, as there will be in practice; this will be observed as a damped wave. The second wave, labelled (4) is a growing wave. The exciting coupler can be expected to excite both waves, the relative amplitude of the two waves depending on the exact geometry, frequency, etc. It appears that close to the coupler, the damped wave (1) is predominant, but that further along the tube the growing wave (4) predominates. This explains why the phase-distance characteristics of Fig. 6 begin, near the exciter, with a small slope, corresponding to the smaller β of the damped wave, and assume a larger slope at large distances, corresponding to the larger β of the growing wave.

By measuring the slope of the phase-distance curve for small and for large distances, approximate values for β_r for each wave may be deduced and compared with the theoretical dispersion curve, as is shown in Fig. 4. In making this comparison, the frequency scale has been fitted by assuming that $\omega_p' = 500$ MHz. While a close fit to the theory is hardly to be expected, it is seen that there is reasonably strong evidence for the stated explanation of the heating effect.

The spatial growth constant, β_i , as determined from the slope of the amplitude-distance curve at large distances from the exciter, is also compared with the theory in Fig. 4. While growth is observed in the expected range of frequencies, and shows the right dependence on frequency, it is clear that numerically, the measured growth constant is very much less than the theoretical value. For $a = 1.27$ cm, the theory indicates a maximum power growth of about 26 db/cm, whereas experimentally the maximum growth rate (at 470 MHz) is no more than 2 db/cm.

It is commonly observed in various beam/plasma measurements that the growth rate is very much less than predicted theoretically. This may be ascribed to a number of factors which are commonly omitted from the analysis, but which have a strong influence in practice. The principal factors involved are collisions, finite temperature, and inhomogeneity. In the present case it is likely that the predominant effect limiting the growth rate is the plasma inhomogeneity. In the surface wave interaction, the fields are concentrated near the plasma-dielectric boundary and it is here, because of the presence of a sheath, that the inhomogeneity is greatest. A further effect is that strong radial electric fields in the sheath are likely to deflect the relatively slow beam electrons away from the surface where the interaction should be strongest.

In the measurements of propagation and growth in the $m = 0$ mode, it is observed that while a growing wave is measured for some distance along the tube, the signal reaches a maximum and then decays past a certain point. This was illustrated in Fig. 4 of QR 5 and was interpreted as being a result of beam break-up due to some signal on the beam having reached large signal level. However, in view of the small growth rates observed in the $m = 0$ mode, it seems unlikely that the effect is due to beam break-up in the $m = 0$ mode. It is possible, however, that it is a result of beam breakup due to growth in some other mode e.g. $m = 1$. Certainly, the limitation of the signal indicates that the steady-state conditions are not uniform along the length of the tube, though whether the nonuniformity is due to beam breakup, or to some other effect, is not entirely clear yet. It is intended to investigate this effect more fully in the coming quarter, and also to make propagation studies in the $m = 1$ mode.

III. ELECTROSTATIC WAVE AMPLIFICATION IN MAGNETOPLASMAS

When the beam and/or plasma have directed or thermal motions in the transverse and axial directions, it is necessary to derive the appropriate dispersion relations using a Boltzmann equation formalism. The results of doing so were discussed rather generally in QR 1 where it was pointed out that, for a high enough value of the parameter (ω_b/ω_c), i.e., the ratio of beam plasma frequency to electron cyclotron frequency, even an ion-neutralized electron beam could be unstable, and that in the presence of a background plasma the instability threshold for the beam density could be reduced. The purpose of this project is to investigate such interactions, and to determine their potentialities for microwave applications.

Numerous theoretical predictions of the instabilities have been made at Stanford and elsewhere. Basically, the theory predicts growth in passbands centered on the electron cyclotron harmonic frequencies $(n\omega_c)$. No further computations will be carried out under this project until our experimental parameters have been measured. Those computations carried out to date are being summarized in a Ph.D. thesis being written by J. A. Tataronis, and which will be completed during the coming reporting period.

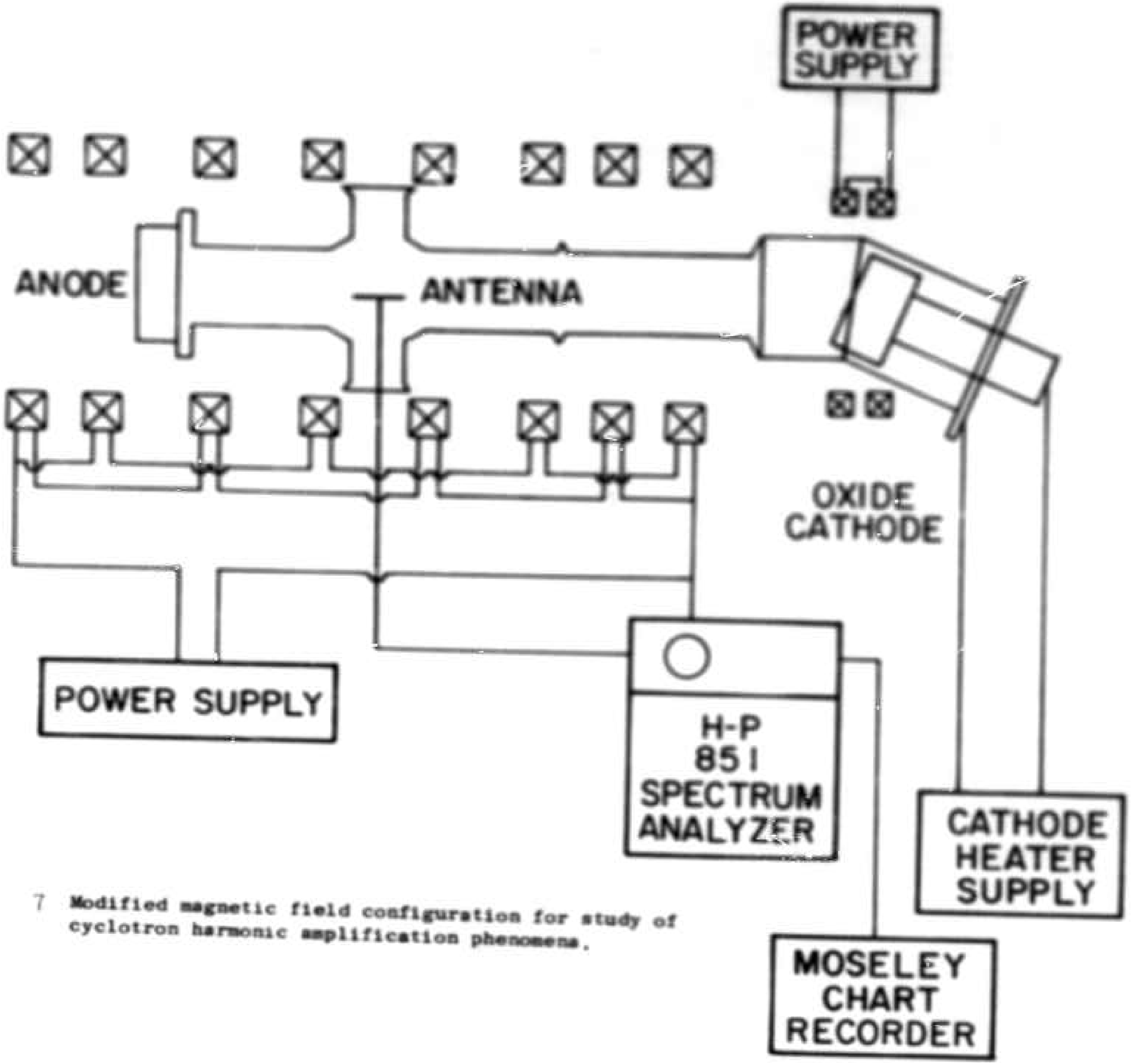
So far, few controlled experiments have been carried out to check the theory, though observations of strong noise emissions from magnetoplasmas containing charged particles with appreciable transverse velocities provide significant support for the existence of the predicted mechanisms. The studies planned under this contract are intended to provide results under refined experimental conditions, and to put the theory on a firm quantitative basis. In particular, we wish to verify the dispersion relation for the realistic case of a delta-function beam interacting with a warm plasma.

(A) Experimental Studies

The aim of the experimental work under this project is to excite growing waves by means of an electron beam injected into the plasma, and to study the variation of the growth rate as a function of the longitudinal and transverse energies of the beam. The first, and simplest, way of imparting transverse energy to the beam is to inject it through an increasing magnetic field into the interaction region. This does not create the delta-function transverse velocity distribution which would be most desirable for checking against theory. A more satisfactory approach is the use of a "corkscrew" injection system.[6] A third method which it was hoped to apply because of its greater flexibility is to impart transverse energy to the electrons by cyclotron heating in a small rf cavity through which the beam passes before entering the plasma region. This has been found extremely difficult to realize for our experimental conditions, however. For convenience in our initial studies, a version of the first method has finally been adopted.

The experimental set-up is as shown in Fig. 7. Eight large coils have been spaced so as to give an axial magnetic field uniform to better than 0.5% over a region of five to six centimeters centered at the probe. To produce a rapidly varying magnetic field close to the cathode, two auxiliary coils have been provided. These control the field in the vicinity of the cathode, but do not disturb the uniformity of the field in the region near the probe by more than two or three percent. The fields due to the two coil systems are controlled by separate power supplies so that the inhomogeneity can be varied relative to the background homogeneous field. The electron beam is injected, through a potential difference, at an angle to the magnetic field. The system is designed so that the Larmor radius of the electrons is large compared to the distance of the grid from the cathode. In this way, the electrons travel in essentially straight lines through the grid region, and then start rotating about the magnetic field lines in the weak field region. The transverse energy, $W_\perp$, is equal to $eV\sin^2\theta$, where V is the potential drop of the grid, and the angle, θ, that the injection system makes with the magnetic field is 30°. Thus, in this case, $W_\perp = W_T/4$, where $eV = W_T$. The electrons are then injected into a high magnetic field region which acts as a mirror to increase the transverse energy of the beam. This system has the advantage that it will allow us to vary the transverse and longitudinal energy of the beam by changing the ratio of the field produced by the large coils to that produced by the small coils.

The theoretical predictions for this type of instability indicate that it will generally be absolute, i.e. signals will grow from noise, and external modulation will not be required to obtain an output.



7 Modified magnetic field configuration for study of cyclotron harmonic amplification phenomena.

This has been confirmed qualitatively by the previous experimental work which it is hoped to refine quantitatively in these studies. For example, in a PIG discharge Landauer[7] observed radiation out to about the 45th harmonic, fitting the relation $(\omega/\omega_c) = n$ to better than 2%. Bekefi and Hooper[8] observed strong cyclotron harmonic radiation from a beam generated discharge in mercury-vapor. As here, they produced the necessary transverse energy by magnetic field inhomogeneity. Ikegami and Crawford[9] have also made measurements of radiation near cyclotron harmonics for a beam-generated mercury-vapor plasma in a magnetic field produced by Helmholtz coils. The mechanism for producing transverse beam energy was again an inhomogeneous magnetic field.

During the previous reporting period, we studied radiation from an argon positive column discharge immersed in the inhomogeneous magnetic field produced by the set-up shown in Fig. 5 of QR 5. Great difficulty was experienced in interpreting the many peaks in the noise spectrum. The work was continued into the present reporting period until the modifications leading to the set-up of Fig. 7 were adopted. Making these has taken up much of the remainder of the quarter, and only preliminary results are available with the new configuration. These will be extended during the coming quarter, and will be reported on in the next QR.

IV. ELECTROMAGNETIC WAVE AMPLIFICATION IN MAGNETOPLASMAS

In the absence of a static magnetic field, interaction of an electron beam with a plasma leads only to electrostatic beam/plasma interactions of the types described in Section II. When a static magnetic field is present, there are additional possibilities of electromagnetic wave interaction. That of special importance under the present contract is the interaction with the right-hand polarized electromagnetic wave known in ionosphere terminology as the "whistler" mode. It has been demonstrated theoretically that under conditions where a beam with transverse energy interacts with the plasma, wave growth in this mode should be possible, and that experimental situations in which this dominates over the electrostatic growth mechanisms occurring at the same time appear to be realizable.[10]

Comparatively little experimental work has been reported so far on propagation of the whistler mode in laboratory plasmas, and none of this seems to have been directed towards observation of wave growth due to interaction with a gyrating electron stream. Such a demonstration forms the primary object of this project. If growth in the whistler mode could be demonstrated, and utilized, it would offer very attractive practical features. In particular, coupling should be facilitated, since the amplification occurs in an electromagnetic mode, i.e., without conversion to an electrostatic mode.

The aims of the present project are as follows: First, to elucidate the theory of the whistler-type instabilities in the simplest geometry, and then to extend this to more realistic physical conditions, and second to demonstrate directly by experiment that growth can occur in this mode.

(A) Theoretical Studies.

No new analyses or computations have been carried out during the reporting period. However, in connection with his Ph.D. thesis preparation, J. A. Tataronis has gathered together details of all our work in this area to date. These will be written up in report form during the coming reporting period.

(B) Experimental Studies.

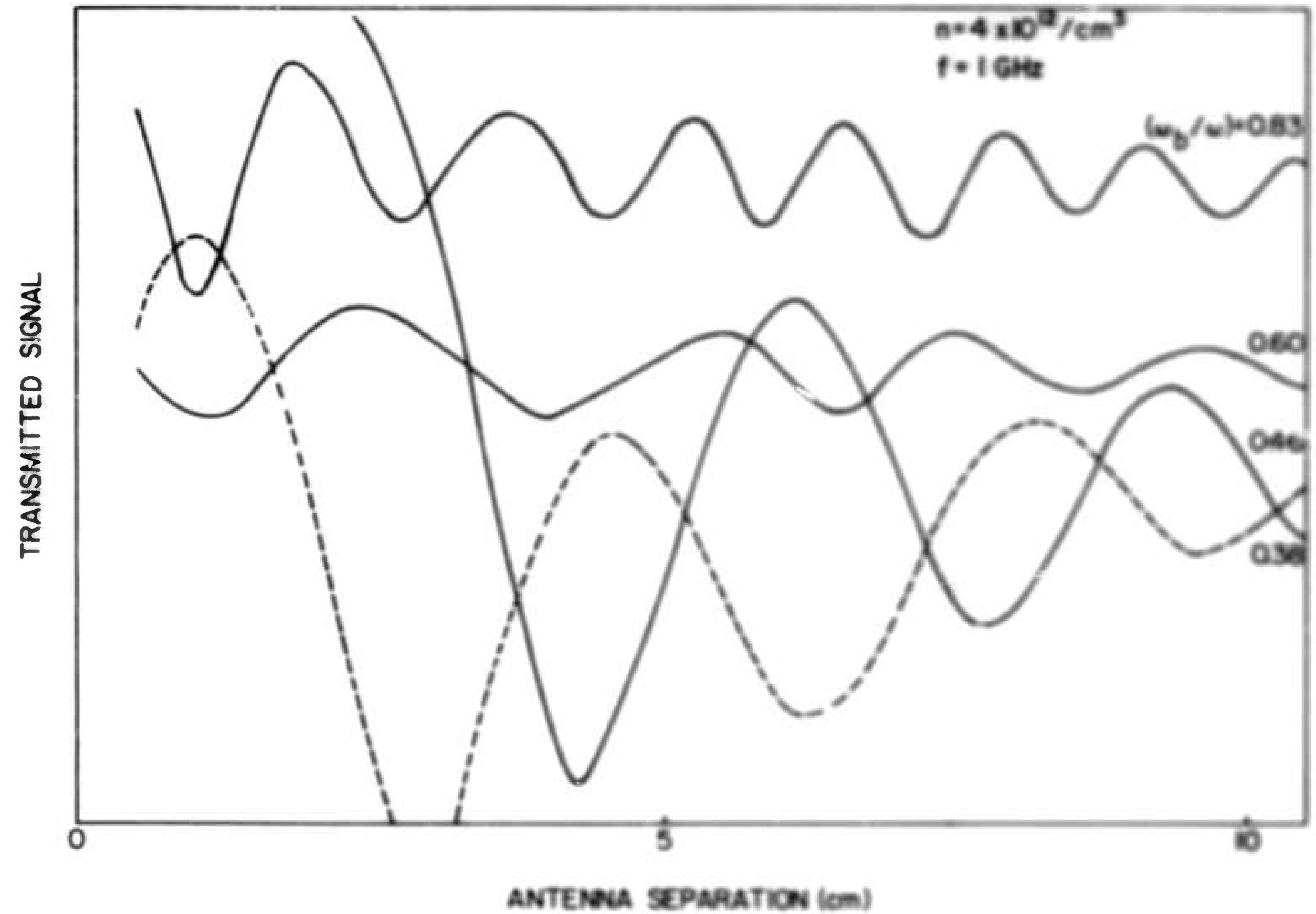
Studies of whistler propagation have continued in the small magnet setup during the quarter. The wavelength of the whistler waves in the plasma was measured using the following technique: The signal coupled between the two antennas was compared with a reference signal which was larger than the transmitted signal, so that the two would add and subtract when in and out of phase. This compared signal was sampled with an electronic circuit that converted the signal occurring during a time interval less than 2 μsec long into a voltage that was displayed on the Y-axis of a graphical recorder. The sampling circuit was synchronized with the pulsed discharge, and adjusted to select specific densities for experimentation. The separation of the two antennae was varied and plotted on the X-axis of the recorder. This technique produced interferograms of the type presented in Fig. 8. The wavelength in the plasma was obtained by measuring the distance between successive maxima (or minima) of the interferograms.

Results obtained from many interferograms are plotted in Fig. 9. The points represent experimental results, while the lines are obtained from the infinite, cold, collisionless, whistler dispersion relation. In normalized form, this is,

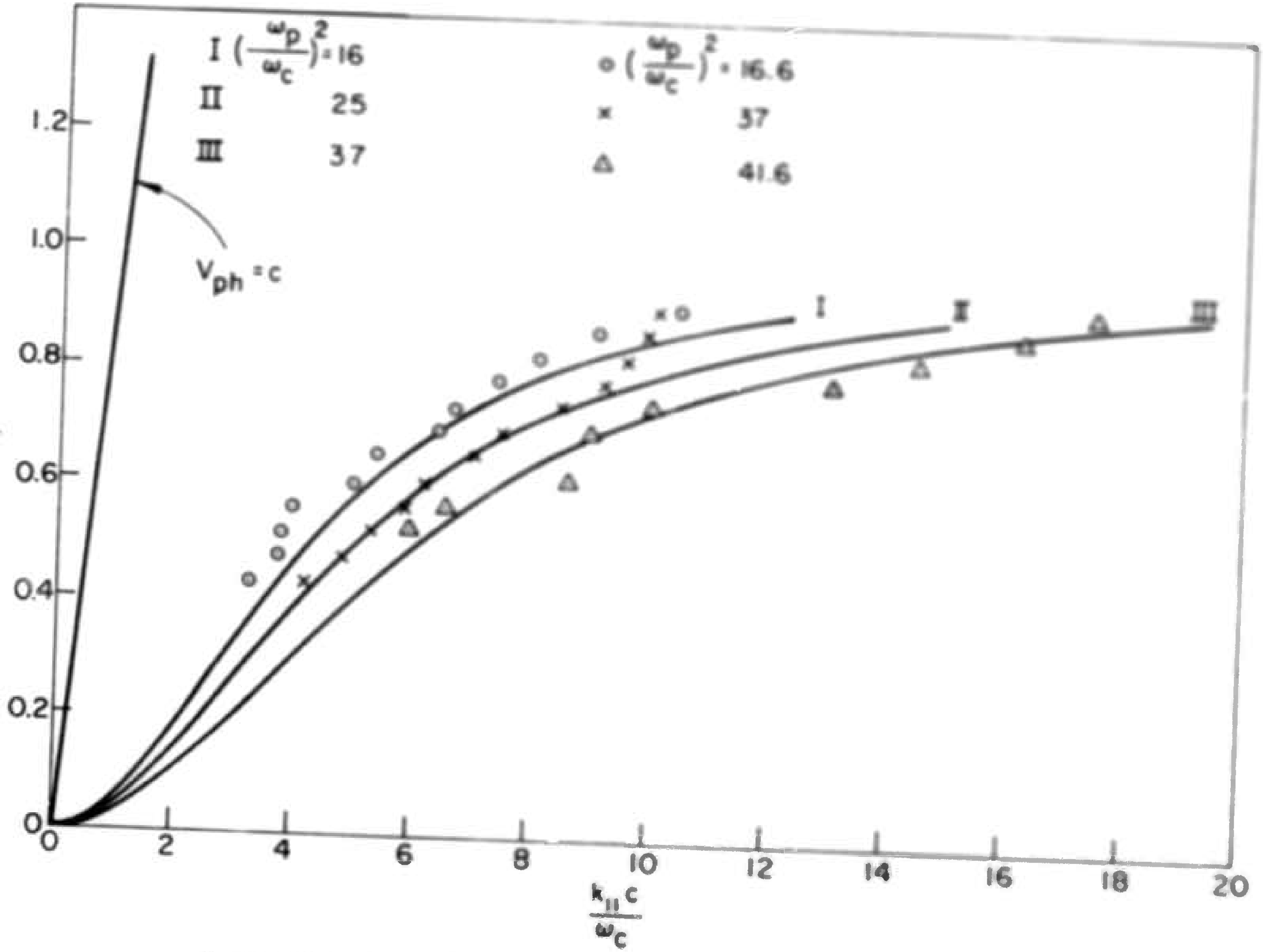
$$\frac{kc}{\omega_b} = \frac{\omega}{\omega_b}\left[1 + \frac{(\omega_p^2/\omega_b^2)}{\frac{\omega}{\omega_b}\left(1 - \frac{\omega}{\omega_b}\right)}\right]^{1/2} . \tag{9}$$

Notice that the agreement is quite good for large values of k, corresponding to short wavelengths in the plasma. At lower frequencies, corresponding to longer wavelengths, the agreement is not as good. This result is to be expected because of the finite size of the experimental apparatus. It was found experimentally, that for wavelengths in the plasmas greater than 3.75 cm (= half the plasma diameter), the finite geometry effects became important, and the infinite plasma dispersion relation was no longer valid.

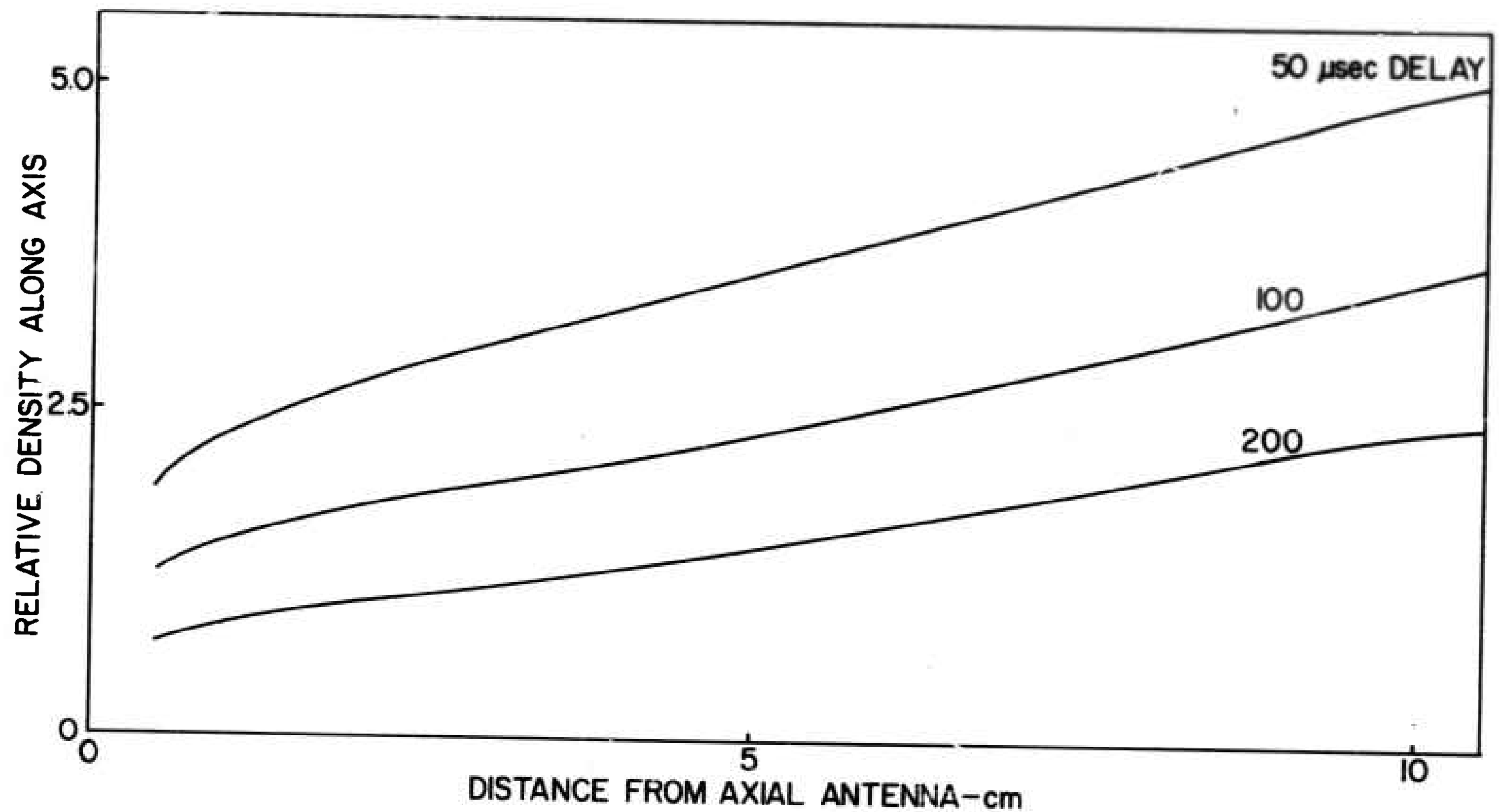
The variation of the wavelength in the plasma visible in Fig. 8 was a result of density gradients in the z-direction resulting from the axial probe. Figure 10 is a plot of the relative density along the axis as a function of the distance from the axial probe at different times in the afterglow.



8 Whistler dispersion measurements: Interferograms of the microwave signal propagated through the plasma.



9 Whistler dispersion measurements: Comparison of theoretical curves (full line) and experimental data.

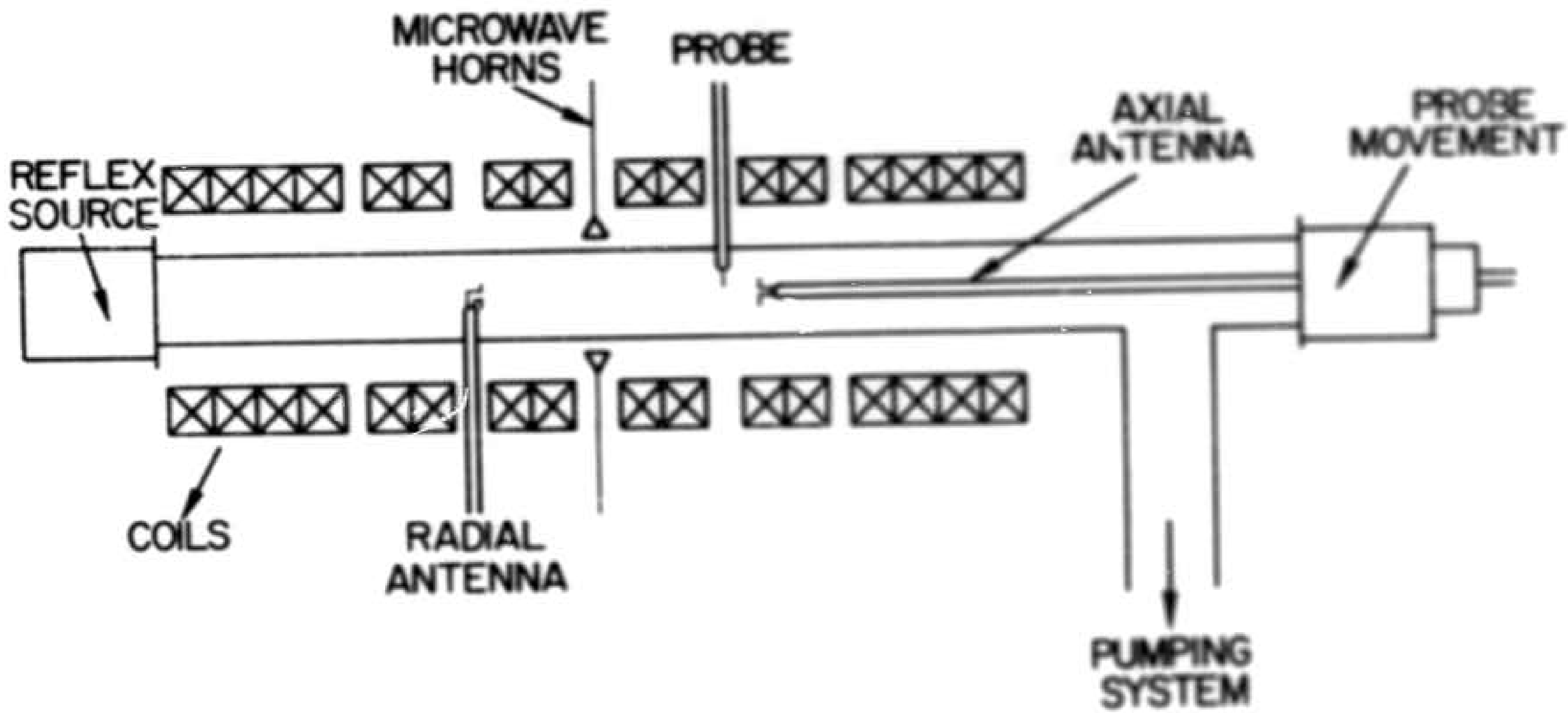


10 Density shadow cast by axial antenna.

Due to a variety of reasons, it was found to be possible to obtain experimental dispersion relations which agreed with theory only over a limited range of parameters. At low plasma densities, or at low magnetic fields, the wavelength in the plasma was too long to be measured accurately with the probe system that was used. The effects of nonuniformities in the magnetic field became very important when the system was adjusted near cyclotron resonance. These effects limited the experimental range of the parameter (ω/ω_b) to $0.4 < (\omega/\omega_b) < 0.9$. Although the maximum density obtainable with the reflex plasma source was greater than $4 \times 10^{13}/cm^3$, it was necessary for the minimum of plasma density at the axis to disappear before experiments could be performed. This limited the maximum plasma density that could be used for experimentation to less than $5 \times 10^{12}/cm^3$. It is unlikely that the maximum plasma density can be increased using this source because, at a plasma density of $4 \times 10^{13}/cm^3$, the gas is nearly fully ionized in the pressure range where the source operates $(0.5 < p < 2$ mTorr).

This series of experiments completes the preliminary whistler studies using the small magnet system. The experimental apparatus used in the small system is currently being transferred to the large magnet, and is nearly ready to begin. A diagram of the experimental apparatus is given in Fig. 11. The experimental arrangement is similar to that used in the small magnet system. The principal differences are: (i) the axial probe is not inserted through the cathode of the pulsed reflex source, and (ii) the radial antenna is moveable, so that measurements of the radial variations of the waves can also be made. As mentioned in the last report, the magnetic field is uniform to 0.25 percent and has a maximum value of 7.7 kilogauss.

The initial experiments performed on the large magnet system in which the plasma is created by an intense rf source have not been successful due to an unexpected complication. The dc power supply for the magnet has, as its controlling elements, three high-power thyristors which are phase-controlled. The intense rf pulses cause the thyristors to trigger at unpredictable times, resulting in a loss of control of the large magnet. It does not seem feasible to shield the magnet power



11 Schematic of high magnetic field set-up for whistler studies.

supply adequately from the intense rf radiation. Consequently, it was decided that the pulsed reflex source would be employed in the new system, while other plasma sources are being investigated.

During the coming quarter, study of whistler wave propagation will continue in the new apparatus. Concurrently, an injection scheme whereby an electron beam with transverse energy can be injected into a plasma will be investigated on the small magnet system. The method uses a parallel injection mechanism, and has been investigated by Dunn and Holaday.[11] A possible disadvantage of the method is that the injected beam is formed in a region of weak field, and injected into a region of strong field, causing a transfer of parallel energy into transverse energy, and a reduction of the cross section of the beam. This point is under consideration in the gun design.

V. FUTURE PROGRAM

Most of the details of our program for the coming quarter have been dealt with in the relevant theoretical and experimental sub-sections of Sections II-IV. Summarizing, the program is as follows:

(i) Beam/plasma amplification with transverse modulation -- Theoretical work will continue on beam/surface wave interactions, first for the $m = 0$ mode, then for the $m = 1$ mode. It is anticipated that our measurements on the sealed-off tubes constructed so far will be completed shortly, and that further studies will be made in a more flexible continuously-pumped system.

(ii) Electrostatic wave amplification in magnetoplasmas -- Further measurements on the noise spectrum due to magnetoplasma wave excitation by electrons with transverse energy will be made in the modified magnetic field configuration described in this report, first with a view to identifying the various frequencies so far observed, then with the aim of verifying the theory quantitatively for a delta-function beam interacting with a cold plasma.

(iii) Electromagnetic wave amplification in magnetoplasmas -- Our studies of the relevant dispersion relations will be extended numerically. A particular point to receive attention is the computation of growth rates of competing wave amplifying processes in the whistler frequency range. Propagation measurements will be extended in the K-band system preparatory to introducing an electron beam with transverse energy to excite wave growth.

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1 June - 31 August, 1967

1. Quarterly Report No. 5 (1 March - 31 May 1967)
   I.P.R. 170 (June 1967).

2. Diament, P., "Inverse Velocity Space Spectra and Kinetic Equations"
   I.P.R. 173 (June 1967).
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13. ABSTRACT

This report describes a program of work on beam/plasma interaction. Both electrostatic and electromagnetic wave amplifying mechanisms are under investigation. For the former, studies in the absence of a static magnetic field are directed towards verifying the theory for the cases of finite beam/infinite plasma, and beam/surface wave amplification, when transverse modulation is applied. Two distinctly different lines are being followed for interactions in the presence of a static magnetic field: Electrostatic cyclotron harmonic wave interaction is being examined, both theoretically and experimentally, and the potentialities of electromagnetic wave growth in the "whistler" mode are being investigated.

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