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Experiments on Wave Interactions Between Plasma and an Electron Stream in a Magnetic Field

J. R. Apel and A. M. Stone

ABSTRACT

Experiments have been conducted on the UHF wave interactions between a plasma and an electron stream (Refs. 1 and 2), and comparisons made between the measured and calculated values of frequencies and wavelengths. The apparatus consists of a plasma source producing a plasma column 1 cm in diameter with n_e adjustable between 10^9 and 10^{13} cm^{-3}; an electron gun yielding 180 ma at 2000 volts, flowing coaxially with the plasma; and a collimating magnetic field of 400 oersted intensity. The theory and measurements show the instability to be due to the interaction of the electron cyclotron wave in the plasma with the "plasma wave" in the beam.

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I. INTRODUCTION

There are several wave mechanisms by which a plasma and an electron beam may interact, and these have been the subject of intensive studies during the past few years. The interactions arise from the coupling of two plasma waves having nearly the same phase velocities. This paper reports on the experimental study of a certain type of interaction.

II. THEORETICAL DISCUSSION

Consider a two-component system consisting of a stationary plasma of plasma frequency ω_p and a streaming component, or beam, of plasma frequency ω_b and velocity v_b. In the presence of a magnetic field, there may exist within the plasma a longitudinal plasma oscillation near the plasma frequency having the dispersion relation $1 - \omega_p^2/\omega^2 = 0$, and a transverse cyclotron oscillation near the cyclotron frequency ω_c having dispersion characteristics given by $1 - \omega_p^2/(\omega^2 - \omega_c^2) = 0$. Similar waves exist in the beam but are Doppler-shifted by an amount kv_b due to bodily transport of the oscillations by the streaming motion. Here k is the wavenumber.

In the case of infinite, uniform geometry, the longitudinal waves in the two components may interact, leading to the two-stream instability (Ref. 3); the transverse waves may also interact, leading to a cyclotron-cyclotron instability (Ref. 4). If the geometry of the system is finite, however, the fringing of electric fields at the boundary introduces some transverse component to the longitudinal oscillation, thus leading to wave propagation and energy transport (Ref. 5). If the phase velocity ω/k of the wave in one component is equal to the phase velocity of the transverse wave in the other component, a coupling between these two waves may arise and a new type of instability may result. It is this type of interaction which forms the basis for the remainder of the discussion.

These considerations may be made more precise by formulating the appropriate boundary-value problem in cylindrical coordinates and treating the beam and plasma as tensor dielectrics (Ref. 4). For the case of a cold beam and a cold plasma of radius r, surrounded by a conducting cylinder of the same size, the dispersion equation takes the form

$$D(\omega,k) = 0 = 1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_b^2}{(\omega-kv_b)^2}$$

$$+\left(\frac{x_{01}}{kr}\right)^2 \left[1 - \frac{\omega_p^2}{\omega^2-\omega_c^2} - \frac{\omega_b^2}{(\omega-kv_b)^2-\omega_c^2}\right] \qquad (1)$$

where x_{01} is the first root of the zeroth-order Bessel function.

Figure 1 illustrates the dispersion characteristics of each wave in each component, without coupling between them taken into account. The values of parameters are those of experimental interest. The generally horizontal lines represent the waves in the plasma while the sloping lines represent those in the beam. The beam waves are labeled "fast" and "slow" according to whether their phase velocity ω/k is greater or less than v_b. Wherever two lines cross, the phase velocities are equal and an interaction is possible. If the slopes $\partial\omega/\partial k = v_{group}$ are oppositely directed in the vicinity of equal phase velocities, energy will be propagated in opposite directions in the two components and a complex frequency $\omega = \omega_r + i\omega_i$ will result, leading to a non-convective instability and to growth in time. If, however, the group velocities of two waves have the same sense near a crossing, a convective instability arises, which may be described by a complex wavenumber and which leads to growth in space. Such is the situation in the

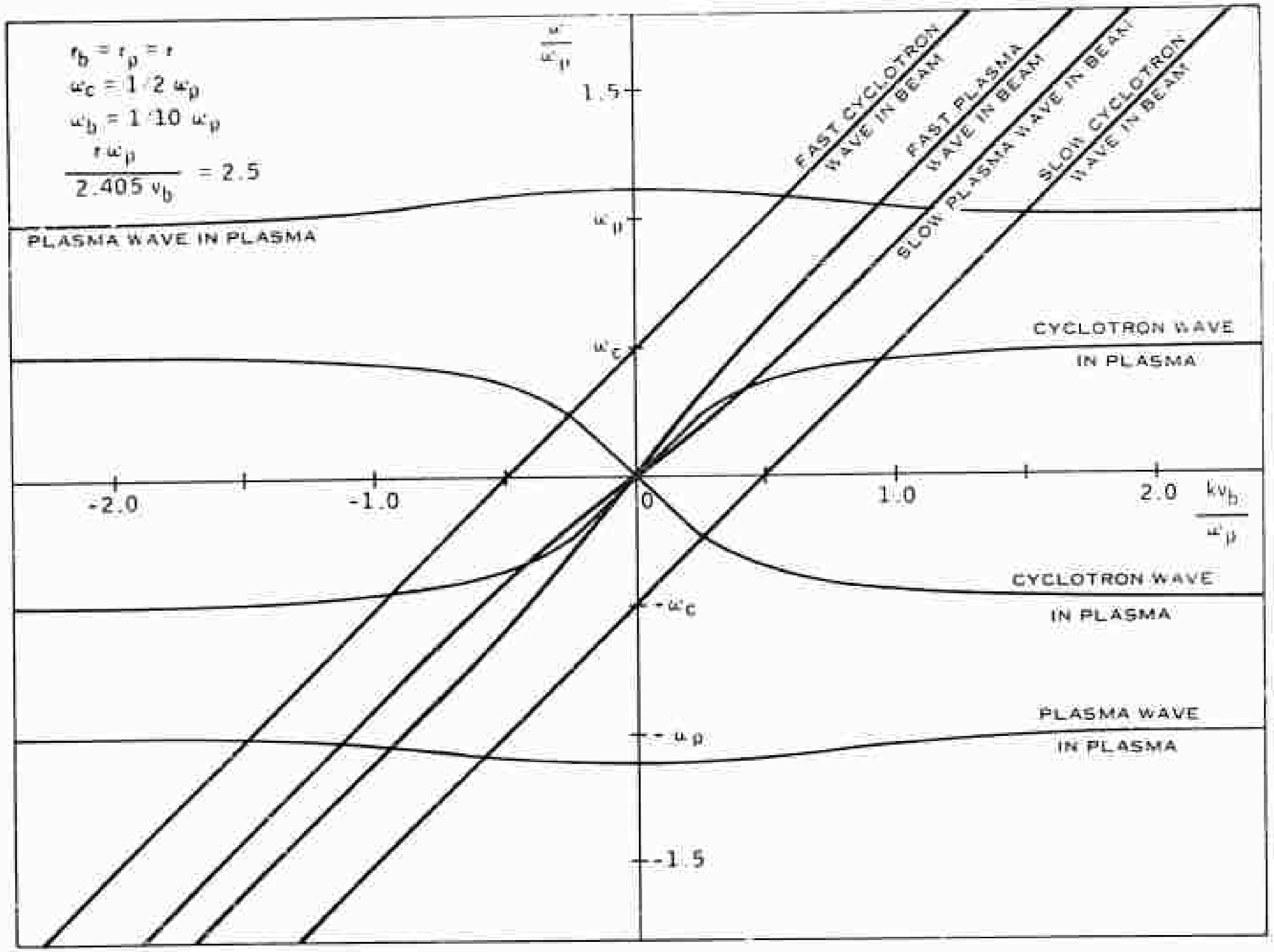

Fig. 1 DISPERSION DIAGRAM OF BEAM AND PLASMA WITHOUT INTERACTIONS; FINITE RADIAL GEOMETRY AND FINITE MAGNETIC FIELD

vicinity of $kv_b/\omega_p = 0.4$ on Fig. 1, where the effect of finite radius has caused the plasma cyclotron wave to have nearly the same group velocity as the slow plasma oscillation in the beam.

If now one solves the dispersion equation with interactions taken into account, a graph similar to Fig. 2 results. This figure shows the upper half-plane of Fig. 1, with complex wavenumber assumed. Re(k) is plotted with solid lines, Im(k) in dotted. The approximate experimental operating points are indicated where $Im(k_1)$ is a maximum.

III. EXPERIMENT

In order to observe the beam-plasma interaction discussed above, we have constructed the experimental apparatus shown in Fig. 3.

At one end is a steady-state PIG-plasma source which generates a plasma column 1 cm in diameter, whose density is adjustable between 10^9 and 10^{13} electrons/cm^3. The electron temperature as determined by Langmuir probes is about 8 eV. The neutral pressure in the interaction region is a few times 10^{-4} torr, resulting in an electron-neutral collision frequency of a few megacycles. Detuning of a resonant cavity through which the plasma flows is used to monitor the electron density continuously, and this density measurement is verified by pulsed Langmuir probe measurements downstream. In general the densities as determined by the two methods are within a factor of two of one another. On the right of the apparatus is the electron gun, which yields 180 ma of beam current at 2000 volts, focussed into a column 1 cm in diameter. The beam flows coaxially with the plasma and is collected within the PIG after traversing some 60 cm of plasma. Modulation between 800 and 3000 mc/s may be applied to the beam by an adjustable re-entrant cavity, but is not essential to the excitation of the interaction. A uniform magnetic field of up to 400 oersted collimates

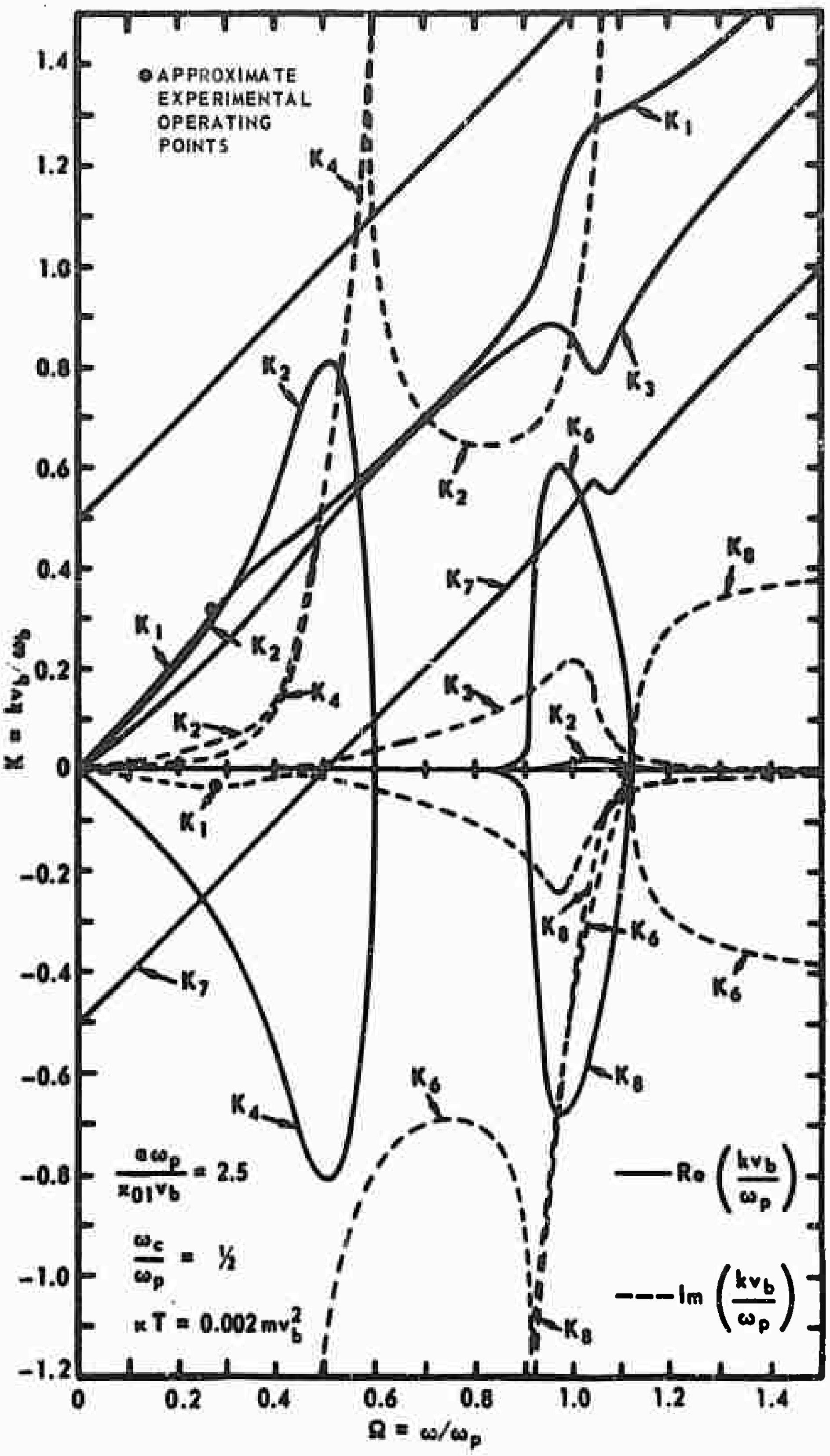

Fig. 2 DISPERSION DIAGRAM FOR BEAM-PLASMA WAVES. FINITE MAGNETIC FIELD, RADIUS, AND TEMPERATURE

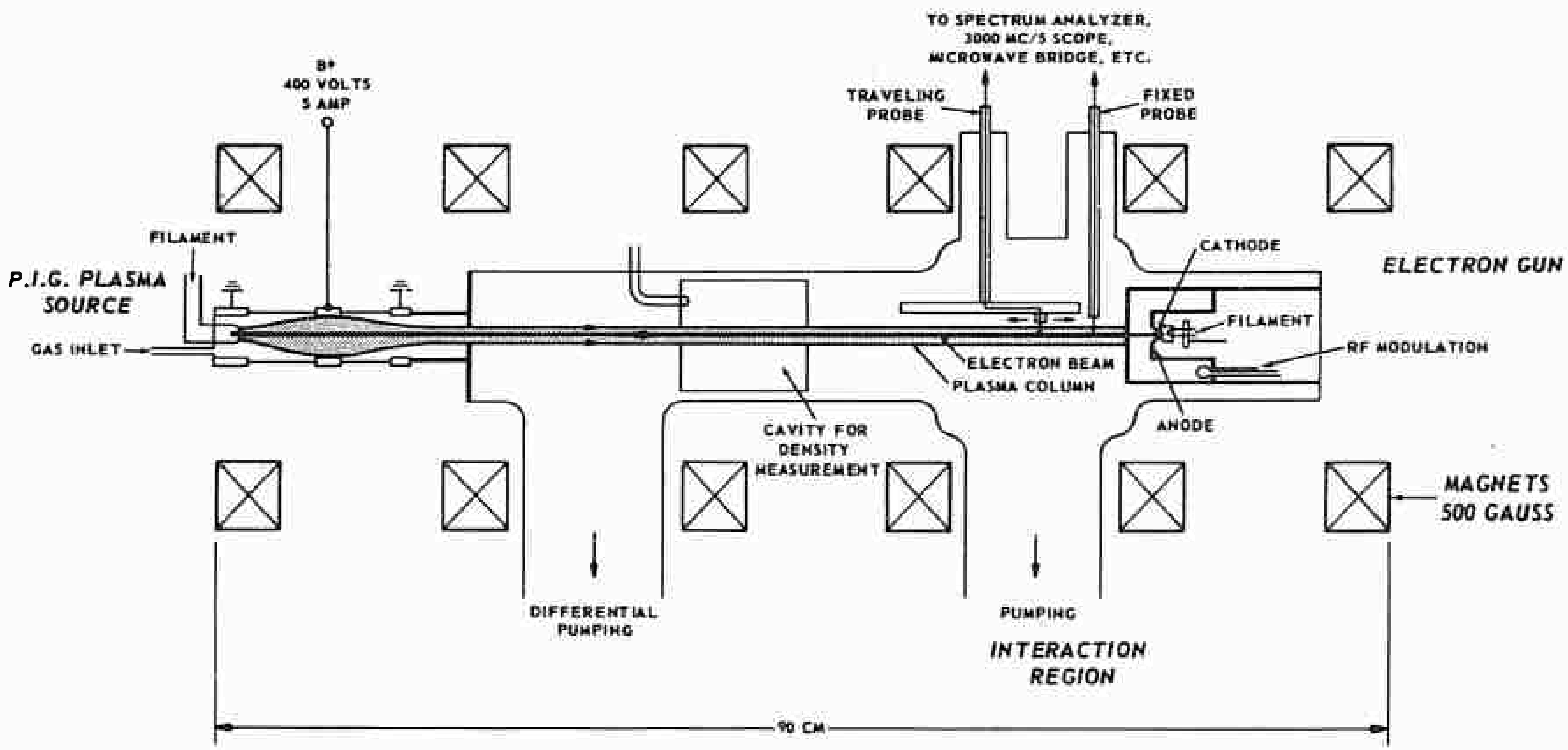

Fig. 3 SCHEMATIC OF APPARATUS - BEAM-PLASMA INTERACTION EXPERIMENT

both beam and plasma. Traveling probes are used to sample the rf signals emitted during the beam-plasma interaction as well as to determine the spatial distribution of electrons. These signals are observed in real time on a 3000 MHz oscilloscope and on a spectrum analyzer. A phase- and amplitude-sensitive coaxial bridge network is used to determine wavelengths and growth rates.

At the start of the experiment, the important plasma and beam properties are known fairly accurately. When the beam is pulsed on, a spatially-growing wave is excited in the plasma under proper conditions of plasma density, magnetic field, and beam voltage. By pulsing the beam for only 1 microsecond, effects such as subsidiary ionization and disruption of the plasma are avoided and the properties of interest are nearly those existing at $t = 0$. The wave frequency is in the UHF region, the oscillations occurring in packets or bursts which give the signal the appearance of amplitude modulation. During any one burst, the wave amplitude quickly reaches a limit (not predicted, of course, by the linear theory above) where it persists for several tens of periods before decaying; the latter is probably due to a combination of interruption of the electron beam by the intense interaction and heavy Landau damping by the turbulently-heated electrons in the plasma. Rather large amplitudes are reached before the limitation; for example, the power picked up by a small probe located at the edge of the plasma is about 0.1 watt when the input dc power to the beam is 80 watts. The probe extracts only a small fraction of the total UHF power; hence, the power level due to the interaction must be in the vicinity of several watts.

The wave exhibits growth in space which is observed to be approximately exponential as one varies the probe position from the muzzle of the electron gun toward the plasma source, much as shown in Fig. 4. This graph given power versus axial distance for four

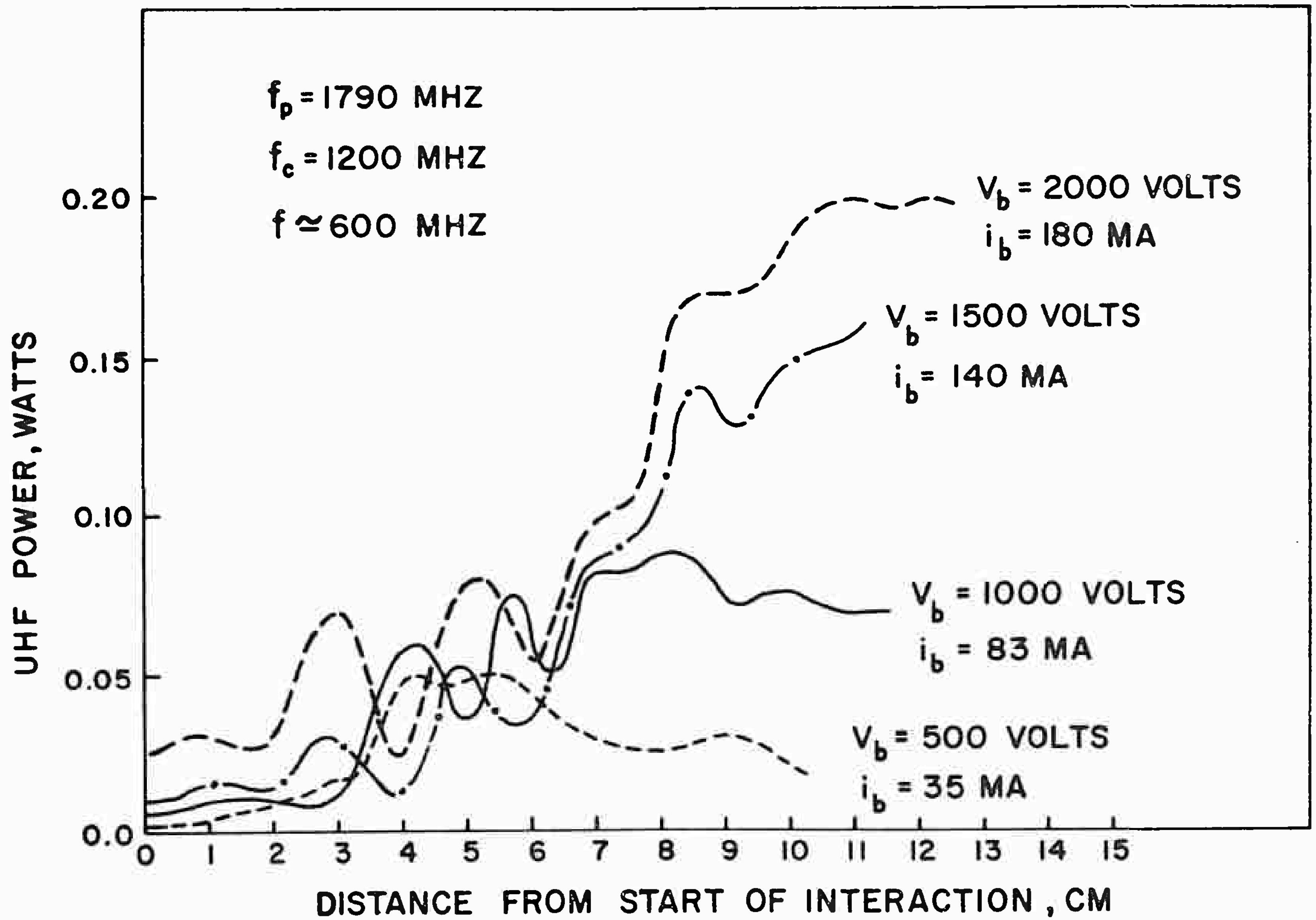

Fig. 4 UHF POWER TO PROBE VERSUS AXIAL DISTANCE

values of beam voltage V_b. The position of the maximum value of power increases as the square root of the voltage, indicating it is associated with the velocity of the wave.

As the plasma density and magnetic field strength are varied, so are the wavelength λ (equal to $2\pi/\mathrm{Re}(k)$) and frequency f at which the interaction occurs, as shown in Figs. 5 and 6. (There is actually a spectrum of frequencies for any set of values of f_p and f_c, leading to a broad line as observed on the spectrum analyzer having a Q of about 10.) The wavelength measurements indicated by dots on Fig. 5 are compared with those computed assuming the wave to have the same velocity v_b as the beam and frequency f; the latter are indicated by squares on Fig. 5. In general, the measured wavelengths imply a phase velocity slightly less than v_b, which is as it should be; the slow plasma wave in the beam travels at a velocity slightly less than that of the beam (Fig. 1). Also shown is the negative of Im(k) (or the axial growth constant) as obtained from the average slope of logarithmic plots of data similar to those on Fig. 4. There is a maximum interaction frequency, f_{max}, beyond which growing waves are no longer observed. In all cases, the interaction frequency is less than either f_p or f_c, implying that the wave must be associated with the propagation of an electron cyclotron wave in the general direction of the magnetic field.

If the beam-cavity modulation feature is used and the modulation frequency is chosen about equal to the frequency f at which the interaction occurs naturally, the Q of the spectral line is increased to about 200. The time behavior of the wave is much less erratic with modulation present, indicating that the broadening existing without modulation is chiefly due to Fourier components arising from the fluctuating wave amplitude.

The same cavity permits a direct check on the interpretation of the interaction as being due to an electron cyclotron wave in

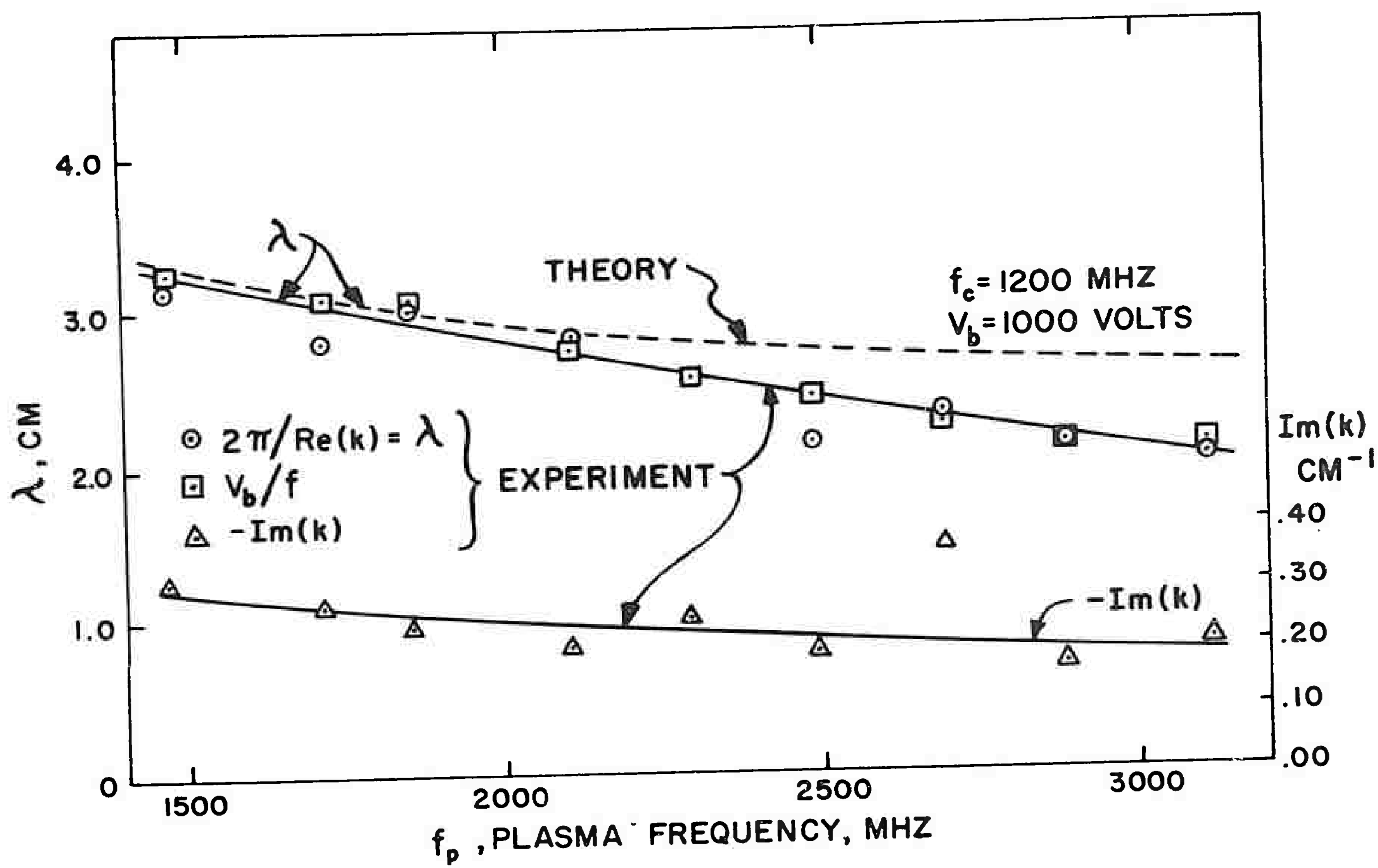

Fig. 5 WAVELENGTH AND AXIAL GROWTH CONSTANT VERSUS PLASMA FREQUENCY

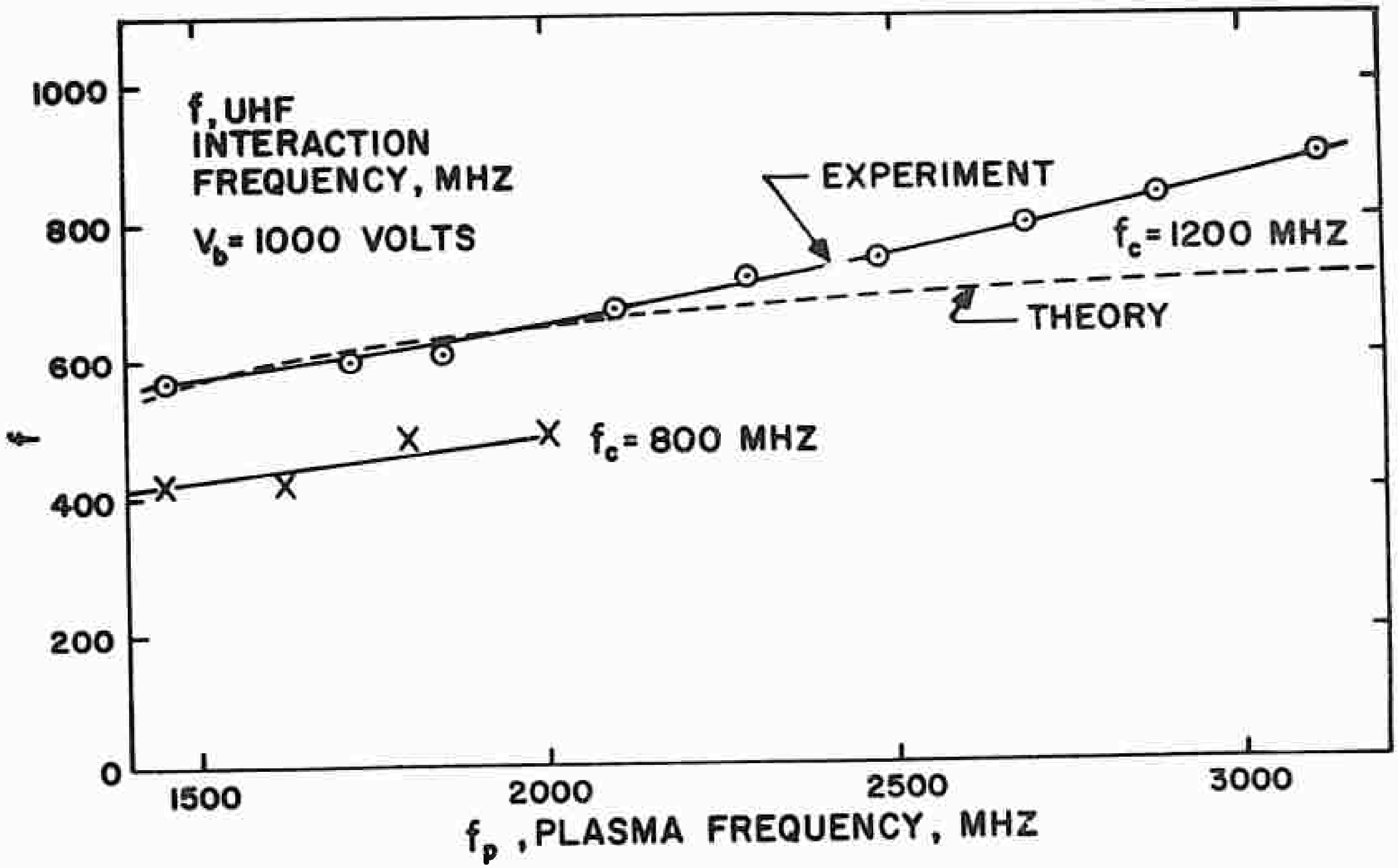

Fig. 6 INTERACTION FREQUENCY VERSUS PLASMA FREQUENCY

the plasma. In the absence of the beam, a cyclotron wave is launched in the plasma column by exciting the cavity, and its phase and amplitude are determined; the excitation frequency is chosen to be the same as the interaction frequency f which would occur at that particular plasma density. Now, when the beam is turned on and the cavity is greatly detuned so as to avoid modulation, it is found that the same phase and wavelength relationships exist in the spatially-growing wave as were possessed previously by the cyclotron wave. In addition, both waves are approximately circularly polarized, as determined by two E-sensitive probes at right angles to both B and to one another.

IV. COMPARISON WITH THEORY

On Fig. 2 are two points labeled "Approximate Experimental Operating Points." These occur at values of Re(k) and ω where Im(k) is a maximum, i.e., at the value of wave number which represents the most rapid growth. A comparison of experimental and theoretical values of these variables is given below for one set of experimental conditions. The agreement is excellent except in the case of Im(k), where thermal or Landau damping has reduced the growth constant below that for the cold plasma case.

	ω/ω_p	$\mathrm{Re}(kv_b/\omega_p)$	$\mathrm{Im}(kv_v/\omega_p)$
Theory	0.29	0.32	-0.036
Experiment	0.26	0.30	-0.026

On Figs. 5 and 6, the curves labeled "Theory" show the calculated functional behavior of f and λ versus f_p, using Eq. (1) and the measured values of density, magnetic field, and voltage. No fitting or normalization of data has been done in making the comparison. It is seen that the theory accounts rather well for the properties of the interaction, with the largest departures occurring at higher plasma densities.

V. SUMMARY

The experiment and theory show the beam-plasma interaction to be a convective instability resulting from the synchronism of a longitudinal plasma wave in the beam with a transverse cyclotron wave in the plasma. This coupling occurs because of the finite radial boundaries. The wave parameters appear to be well described by the theory.

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