PLASMA DYNAMICS

This heading covers all of the work that is supported in part by the National Science Foundation and is under the over-all supervision of the Plasma Dynamics Committee of the Massachusetts Institute of Technology. The general objective is to combine the technical knowledge of several departments, in a broad attempt to understand electrical plasmas, to control them, and to apply them to the needs of communication, propulsion, power conversion, and thermonuclear processes.

(The members of the Plasma Dynamics Committee are: Prof. S. C. Brown (Chairman), Prof. D. J. Rose, Prof. A. H. Shapiro, Prof. L. D. Smullin, Prof. H. J. Zimmermann.)

XIII. PLASMA PHYSICS[*]

Prof. S. C. Brown	F. X. Crist	D. T. Llewellyn-Jones
Prof. G. Bekefi	H. Fields	J. J. McCarthy
Prof. D. R. Whitehouse	E. W. Fitzgerald, Jr.	W. J. Mulligan
M. L. Andrews	W. H. Glenn, Jr.	J. J. Nolan, Jr.
V. Arunasalam	E. B. Hooper, Jr.	G. L. Rogoff
J. F. Clarke	J. C. Ingraham	F. Y-F. Tse
J. D. Coccoli	P. W. Jameson	R. E. Whitney
	R. L. Kronquist	

RESEARCH OBJECTIVES

The aim of this group continues to be the study of the fundamental properties of plasmas with particular emphasis on plasmas in magnetic fields. In emphasizing our interest in high-density plasmas, we have spent a great deal of effort on production of plasmas of high-percentage ionization at low pressures under steady-state conditions, the achievement of which will allow us to carry on the fundamental studies in which we are most interested.

We are also studying ways of determining the characteristics of plasmas by means of microwaves and infrared optics. Along with these production and diagnostic studies, we are continuing measurements on the fundamental physics of loss and gain mechanisms of electrons in plasmas in magnetic fields. Emphasis is also being placed on the study of microwave radiation from plasmas, with and without magnetic fields, both as a tool for measuring the plasma temperature and thermal properties and as a means of understanding more about the motion of electrons and ions in magnetic fields.

Theoretical work has been concentrated on the study of waves in plasmas and of statistical theories of the nature of a plasma.

S. C. Brown

A. LOW-FREQUENCY PLASMA WAVES

A study has been initiated into the response of plasmas at frequencies much below the electron plasma frequency. Our object is to establish longitudinal ion plasma waves

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in a plasma column and measure their propagation and attenuation characteristics. The experimental arrangement shown in Fig. XIII-1 has been built and is at present under test.

The fundamental idea behind the experiment is to produce a plasma column with cw microwave power into the TE_{111} mode of the cavity. The frequency is adjusted to the electron-cyclotron frequency for resonance heating at low gas pressures. A small modulation is then impressed on the microwave power to vary the electron heating within
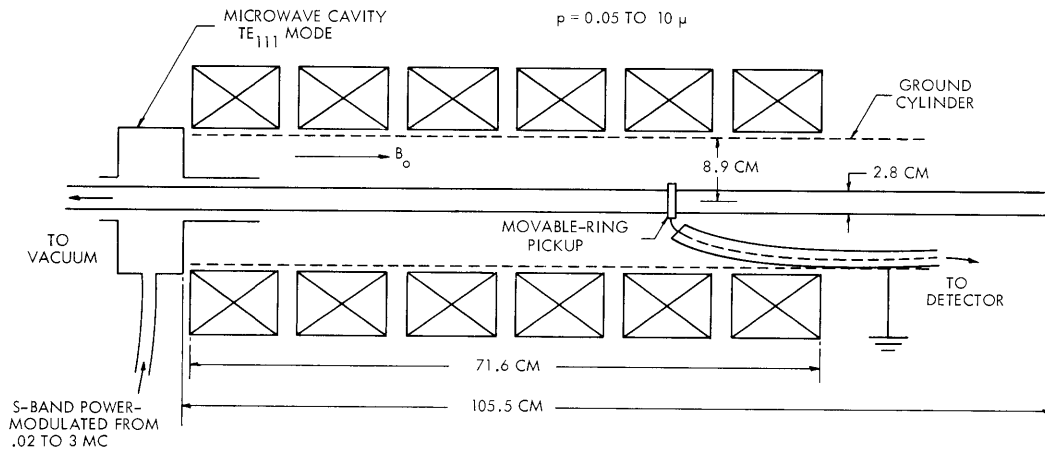

Fig. XIII-1. Experimental apparatus.

the cavity. As the electron energy is varied, the ionization frequency should also be modulated, and hence there will be a local modulation in the electron and ion density. Simple calculations of the ion plasma wave show that for frequencies of approximately 1 mc the wavelength of the ion (and electron) density perturbations can be made as small as a few centimeters, and we should observe a definite wave propagating down the column.

The presence of the wave is particularly easy to determine by measuring the potential that is external to the plasma column at the modulation frequency. Typical data are shown in Fig. XIII-2.

The appearance of the ac potential at the modulation frequency seems to be associated with the flow of charges in the body of the plasma, and because of the extremely long wavelength, it must be a flow of the hot electrons rather than the cold ions. Since the electron plasma wave is attenuated for frequencies below ω_p, we were encouraged to re-examine these waves with particular reference to the mechanism for transport of energy. The normal Boltzmann formulation for electron waves is solved for the perturbation of the distribution function away from some equilibrium distribution. Coupling
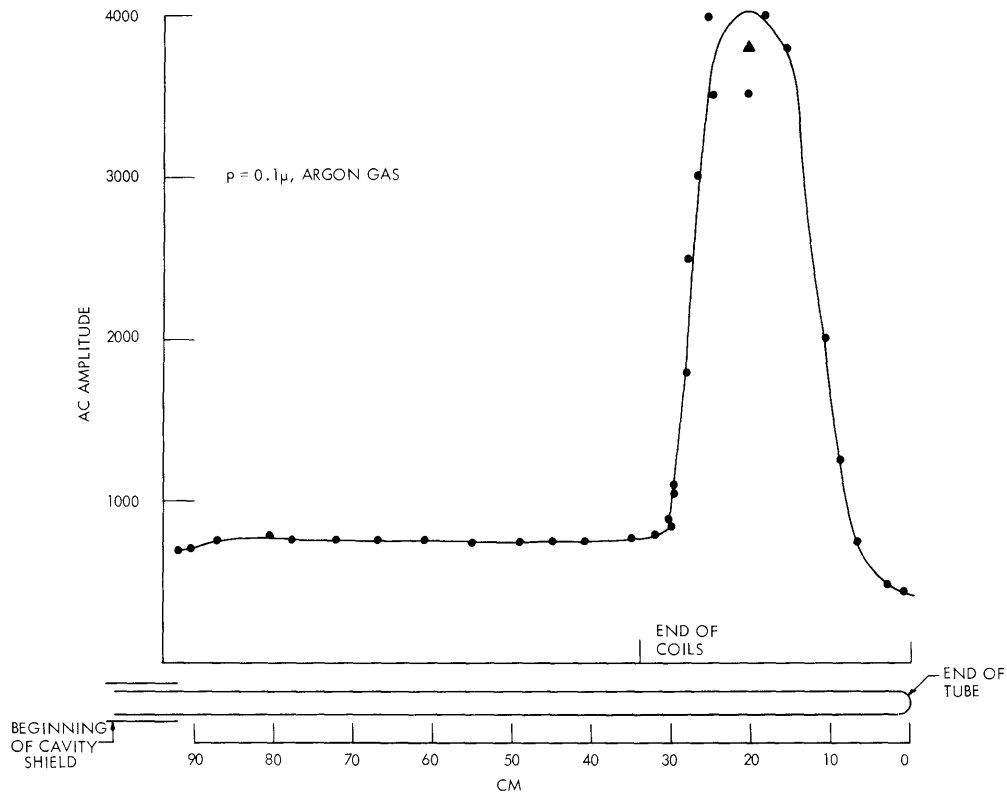
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Fig. XIII-2.   A-C amplitude of 1.1-mc signal on movable ring pickup when S-band power into cavity is modulated at 1.1 mc.

this result with Poisson's equation, we get the dispersion relation (assuming $\nu_c = 0$)

$$1 = \frac{\omega_p^2}{n_o} \int_{-\infty}^{\infty} \frac{f_o \, dv}{(\omega - k \cdot v)^2} \, . \tag{1}$$

The difficulties of this integral are associated with the pole at $v = \omega/k$ and lead to the phenomenon of Landau damping. If we approximate the denominator for small velocities, we get

$$\omega^2 = \omega_p^2 + 3k^2 \langle v \rangle^2 . \tag{2}$$

This steady-state dispersion, however, cannot be valid for the more complicated boundary-value problem in which the electron energy is periodically varied at some plane. The propagation characteristic will, in fact, depend on the particular variation of the distribution function, and also on the unperturbed distribution function.

At this point, therefore, we switch to a hydrodynamic approach that assuredly will miss Landau damping but, on the other hand, will show how momentum and energy are transported in this longitudinal wave. The derivation starts with the first four moments of the transport equation. For simplicity, we assume that electrons collide with neutrals and that it is possible to define a local temperature T associated with a Maxwellian distribution of velocities. This derivation thus differs from the Boltzmann approach, which actually tries to solve for the local distribution.

$$\frac{\partial n}{\partial t} + \overline{\nabla} \cdot \overline{\Gamma} = 0 \tag{3}$$

$$\frac{\partial \overline{\Gamma}}{\partial t} + \overline{\nabla} \left(\frac{ne\ T}{m}\right) + \frac{ne}{m}\ \overline{E} = -\nu_c \overline{\Gamma} \tag{4}$$

$$\frac{\partial}{\partial t} \frac{3}{2}\ (nT) + \overline{\nabla} \cdot \overline{H} + \overline{\Gamma} \cdot \overline{E} = -\ ng\ \nu_c \frac{3}{2}\ (T-T_{gas}) \tag{5}$$

$$\frac{\partial \overline{H}}{\partial t} + \overline{\nabla} \frac{5}{2}\ \frac{ne\ T^2}{m} + \frac{5}{2}\ \frac{ne\ T}{m}\ \overline{E} = -\ \nu_c \overline{H}, \tag{6}$$

where

$n = $ particles/M^3 $\nu_c = $ collisions/sec

$\overline{\Gamma} = $ particles/M^2 sec $g = $ energy-loss parameter

$\overline{H} = $ volts/M^2 sec $\overline{E} = $ volts/M

$T = $ volts

One can derive Eq. 2 from Eqs. 3 and 4 by making an assumption about the temperature variation in the longitudinal wave, that is, either assuming it to be isothermal or adiabatic, and linearizing the equations with small perturbations of the variables. A more complete analysis is made possible by assuming an arbitrary variation in the temperature, and by linearizing all four equations. For small-signal analysis, we assume that

$$\overline{H} = \underline{\overline{H}}e^{j(\omega t - kx)} \qquad\qquad T = T_0 + \underline{T}e^{j(\omega t - kx)}$$

$$\overline{\Gamma} = \underline{\overline{\Gamma}}e^{j(\omega t - kx)} \qquad\qquad n = n_0 + \underline{n}e^{j(\omega t - kx)}$$

$$\overline{E} = \underline{\overline{E}}e^{j(\omega t - kx)}$$

Now we set the collision frequency equal to zero, even though this is contrary to our assumption of a maintained local Maxwellian distribution. The character of the resulting waves will thus become evident, and we can add collisional damping later. The determinant of the linearized equations, although rather complex, results in a dispersion relation that, when written in nondimensional form, is

$$K^4 + (1-2W^2) K^2 + \frac{3}{5} (W^4 - W^2) = 0, \tag{7}$$

where $W^2 = \omega^2/\omega_p^2$, and $K^2 = k^2(eT_o/m)^2/\omega_p^2$. There are two waves associated with Eq. 7, both of which are shown in Fig. XIII-3. Wave I is like the normal electron plasma wave, while wave II propagates down to zero frequency. The ratio of heat flow H to particle flow Γ for these waves is

$$\frac{H}{\Gamma T_o} = \frac{3}{2} \frac{W^2 - 1}{K^2} . \tag{8}$$

For wave II, the heat flow is zero at $\omega = \omega_p$, and the wavelength is finite. At very low frequencies, wave II has a large wavelength and phase velocity equal to the adiabatic electron sound velocity. This result seems to predict closer correlation with our experimental results than Eq. 2.

The presence of two electron waves is somewhat plausible, since we know that it is physically possible to excite independent variations in electron density and temperature at some plane in the plasma, and thus two waves will be needed to satisfy these boundary
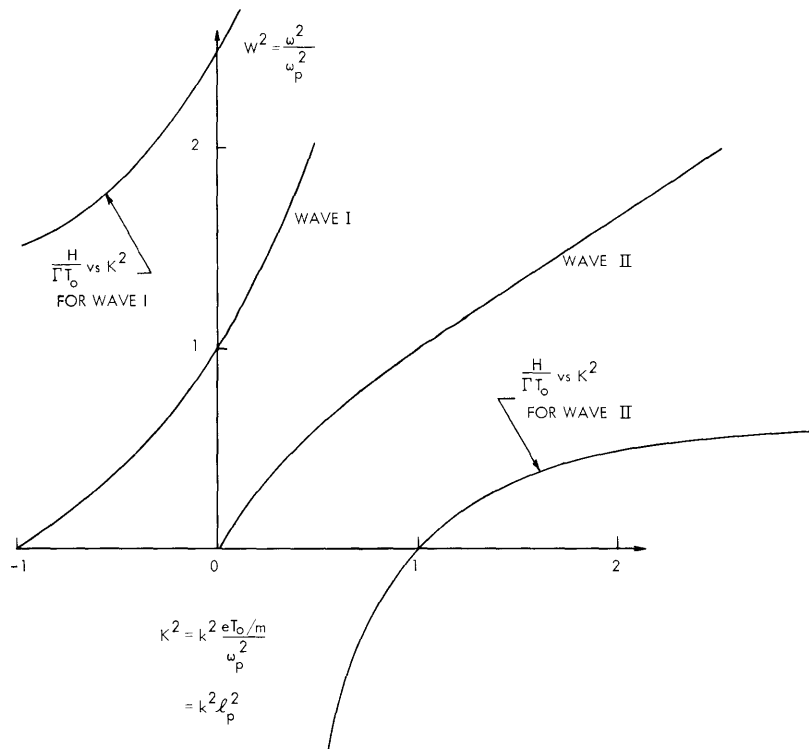

Fig. XIII-3. Waves associated with ω.

conditions. Experimental and theoretical work is continuing.

D. R. Whitehouse, P. W. Jameson

B. DECAMETER RADIATION FROM JUPITER

This report is a summary of a paper that has been submitted for publication to Nature.

The observed correlation between solar-flare activity and intense radio bursts from Jupiter in the 5-38 mc region has prompted several suggestions about the origins of this radiation.[1-3] With the premise that the radioactivity is brought on by sudden eruptions of fast solar electrons as they arrive at Jupiter, we have shown that an existing theory[4-6] for maserlike amplification of synchrotron radiation from electrons with a non-Maxwellian energy distribution orbiting in the Jovian magnetosphere can provide a quantitative model for the emission.

The theory predicts a narrow frequency band of amplification near the local electron gyrofrequency, but the intensity predicted for the second and higher harmonics is smaller than that of the fundamental by more than four orders of magnitude. Thus the appearance of a single band of radiation should not rule out the synchrotron mechanism, as has been suggested.[2]

G. Bekefi, J. L. Hirshfield

(Dr. J. L. Hirshfield is in the Department of Physics, Yale University.)

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