CESIUM PLASMA EXPERIMENTS

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N. D'Angelo

I. Introduction

Since the early years of work with plasma devices it has been recognized that instabilities almost invariably arise in plasmas. Loss rates have been measured largely in excess of those predicted on the basis of the so-called "classical" diffusion theory. In practically all cases the production of plasma requires passage of currents through the gas to be ionized, and it has been speculated that the currents themselves are responsible for the plasma losses. This particular branch of plasma physics has been treated, among others, by L. Spitzer (1) and Bernstein et al. (2). Whether passage of currents along the magnetic lines in machines such as stellarators are responsible for the observed "pump-out" phenomena is indeed still an open question.

A few years ago investigation was started at several laboratories of so-called "quiescent plasmas", i.e. of plasma devices where no current is required to ionize the gas and which, therefore, could perhaps be expected to be free from "anomalous diffusion", instabilities, unwanted oscillations, and noise.

One interesting approach to this problem was proposed in Princeton by W. Bernstein (3). A plasma of moderate (10^9 to 10^{10} cm^{-3}) density and moderate per cent ionization could be produced by the radioactive decay of Kr^{83M}, obtained by neutron irradiation of Se^{82}. The choice of Kr was determined by the requirements that the radioactive material be an inert gas and the products of radioactive decay low-energy electrons, with little γ activity, to minimize health hazard. The half-life of the activity should be long enough to allow transportation of the irradiated material to the stellarator and yet short enough to give a high specific activity. The proposed experiment seemed particularly significant because it would eliminate some theoretically possible sources of electrostatic instabilities in the investigation of plasma confinement. However, it was not pursued any further.

A second approach, which was taken up at several laboratories almost at the same time, made use of the results obtained in the 1920's by I. Langmuir and co-workers [4]. They had found that when a stream of neutral cesium atoms is directed on a tungsten surface at a temperature of $\sim 1000^{\circ}C$ or larger, practically all cesium atoms emerge as ions from the surface. This phenomenon occurs because the ionization potential of the cesium atoms is smaller than the work function of tungsten. It is observed also with other combinations of gases and metals, with the same relation between the ionization potential of the gas and the work function of the metal. So extensive, clear and complete was the work of Langmuir and co-workers that no attempt will be made here to give even a brief description of their experimental methods or a summary of their results. The reader is referred to their original papers. It is somewhat surprising that about three decades had to pass before Langmuir's discovery was put to any use in the production of a laboratory plasma which would exhibit a "quiet" behaviour. The only addition, in principle, to Langmuir's original set-up was in making use of a magnetic field (usually of a few thousand gauss) to confine radially the plasma produced at the tungsten surface. This was done quite recently at M.I.T., Princeton, Hughes Research Laboratories, and Stanford, where cesium plasma devices were built at about the same time. Devices of the same type are under construction or almost completed also at other laboratories (Munich).

The present paper is intended as a review of the work carried out with cesium and potassium plasmas. Section II gives a description, by no means complete, of the type of cesium and potassium plasma devices built in Princeton (Q-1 and Q-3). Section III is devoted to the experiments performed in alkali-metal plasmas. Finally, section IV adds a few words on future experiments which appear to be feasible. The production of a cesium or potassium plasma in a stellarator geometry is also briefly considered.

II. Description of typical plasma devices

This section is intended as a general illustration of the kind of devices used in the production of cesium and potassium plasmas. It is by no means complete and for more specific details the reader is referred to reference (5).

Fig. 1 shows a schematic of the type of experimental set-up in use at Princeton (Q-1 and Q-3). Two hot tungsten plates are located at the opposite ends of a cylindrical vacuum vessel. They are heated by electron bombardment to temperatures of the order of $2300^{\circ}K$. A neutral cesium or potassium beam from an atomic beam oven impinges on the center of one of the two plates. The alkali-metal atoms are ionized by the tungsten plate which is also hot enough to emit an electron flux of approximately the same magnitude of the flux of neutral atoms. Sheaths, with properties depending upon the balance between electron and ion fluxes, will form at each plate. Beyond the sheath regions is a neutral plasma which is confined radially by a longitudinal magnetic field. The tungsten plates are ellipses with a minor axis of ~ 3 cm, oriented at 45° to the axis of the device. Their projections on a plane perpendicular to the lines of force of the magnetic field are circles of approximately 3 cm in diameter. The distance between the two tungsten plates can be varied and is usually kept between 0.5 and 1 meter. The walls of the vacuum chamber are cooled to approximately $-10^{\circ}C$ to condense the neutral cesium or potassium. With a neutral background pressure of $\sim 10^{-6}$ mmHg these devices are capable of producing plasmas with percentage ionizations of 30 to 40 % at ion densities in the low 10^{10} cm^{-3} range and essentially 100 % at densities of about 10^{12} cm^{-3}. The electron and ion temperatures are presumably very close to the temperature of the tungsten plates, i.e. about 0.2 eV. Measurements of electron temperatures by means of Langmuir probes give values generally very close to the above figure. The magnetic fields employed to radially confine the plasma in the Princeton devices go up to ~9000 gauss, with a spatial uniformity in the volume of the plasma of ~5 %, for Q-1, and up to 16000 gauss, with a spatial uniformity of better than 0.5 % for Q-3. In both cases the magnetic fields are steady (D.C.) fields. The Q-3 machine is also equipped to operate with a pulsed magnetic field up to ~35000 gauss and duration of about of 1 sec.

Theoretical descriptions of the plasma produced in such devices have been given in references (5), (6), and (7). In all three references the treatment is based on the Boltzmann moment equations. In references (5) and (6) the following assumptions are made:

a) the ion and electron temperatures are equal and constant throughout the plasma column,

b) plasma diffusion is due only to electron-ion collisions,

c) like particle collisions are unimportant, and

d) volume recombination proceeds as αn^2, where α is the recombination coefficient and n the ion density. The recombination coefficient α is taken to be independent of ion density.

These assumptions cannot be discussed here. The reader is referred to references (5) and (6) for further details. Suffice it to say that on this basis, using a narrow source of Cs impinging on the plate, one obtains a radial distribution of particle density over most of the plasma column of the type $n \sim (\frac{1}{r})^{1/4} e^{-r/2R}$, where r is the radial coordinate and R is related to the magnetic field B, the recombination coefficient α, the temperature T, and the resistivity η, in the following manner:

$$\frac{1}{R} = B \left(\frac{\alpha}{\eta\, kT}\right)^{1/2}$$

The theoretical treatment of reference (7), on the other hand, makes no use of the assumption that ion and electron temperatures are constant throughout the plasma column and actually arrives to the conclusion that temperature variations are in general not at all negligible. This last conclusion nevertheless seems to be to some extent contradicted by Langmuir probe measurements of electron temperature. Perhaps one reason for this discrepancy lies in the fact that no account was taken in reference (7) of the heat conductivity along the magnetic lines of force which tends to keep the plasma temperature close to that of the tungsten plates.

III. Experiments with alkali-metal plasmas

In the present section a summary is given of the experimental work carried out so far with the alkali-metal plasma devices. It is impossible to go into the details of each experiment and it will be necessary to refer the reader to the original papers or progress reports. Before discussing the actual experiments, it will be perhaps worthwile to remark explicitly that the peculiar character of the alkali-metal plasmas (their "quiescence") played a determinant role in the completion of most of these experiments. This applies in particular to the case of wave excitation and propagation of section III.b). The almost complete absence of "noise" made the detection and study of low-frequency waves particularly easy. Similar considerations should apply also to the experiment of beam-plasma interaction of section III.d). Unfortunately, one of the experiments of section III.a), that of passing a current throughout the entire plasma column in order to observe a transition from the "classical" diffusion of references (6) and (10) to "enhanced" diffusion, does not seem to have yielded entirely clear-cut results. It is perhaps interesting to remark that this was the only experiment performed with this type of device in which a deliberate attempt was made to introduce violent instabilities in a plasma by itself "quiescent".

The material of the present section is divided as follows:

a) Experiments of plasma diffusion across a magnetic field,
b) Excitation and propagation of low-frequency waves,
c) Spectroscopy experiments,
d) Beam-plasma interaction.

Any consideration of other experiments which still appear feasible in alkali-metal plasmas is deferred to section IV.

a) Diffusion experiments

The problem of plasma diffusion across a magnetic field dates back to the early days of thermonuclear research. Review articles on plasma diffusion across a magnetic field have become available (8), (9), and it is not intended here to treat the subject to any larger extent than required by its connection with the topic of the present paper.

Diffusion experiments in highly-ionized alkali-metal plasmas in which the only collisions of importance are those among charged particles were carried out almost simultaneously at Hughes Research Laboratories, by Knechtli and Wada [10], and in Princeton, by D'Angelo and Rynn [6]. The method employed was essentially the same as that used in plasmas of low degree of ionization by Neidigh and Simon [11]. Radial density profiles were measured with Langmuir probes and the diffusion coefficients (absolute values and dependence on magnetic field) obtained from the slopes of the profiles. As an illustration of typical results, in Fig. 2 a graph is given of the quantity 1/R, defined in section III, vs. magnetic field. In these diffusion experiments it was found that, when no current is passed through the plasma, diffusion seems to proceed according to the predictions of the "classical" theory ($D_\perp \sim 1/B^2$). Also, the magnitude of the absolute value of the diffusion coefficient is in agreement with the results of the "classical" theory based on ion-electron collisions.

A natural next step seemed to be an attempt to observe a possible transition from "classical" to "enhanced" diffusion when a relatively large current is passed throughout the all plasma column. Experiments along these lines were conducted by Rynn [12], but their interpretation might not be unique [13].

b) Excitation and propagation of low-frequency waves

Under this heading come three different experiments conducted in Princeton.

In the first one, by D'Angelo and Motley [14], an electron current was drawn along the lines of force of the magnetic field over a very small part of the plasma cross section. It was observed that if the electron drift velocity exceeds ~10 $v_{i\ th}$ ($v_{i\ th}$ = ion thermal velocity), the plasma exhibits oscillations. The frequency of the oscillations is slightly in excess of the ion cyclotron frequency, both in Cs and in K (see Fig. 3). It was soon realized that the drift velocity μ of the electrons required to excite these waves is well below the value $\mu \approx v_{e\ th}$ ($v_{e\ th}$ = electron thermal velocity) predicted by numerous theories of ion wave instabilities [15], [16], [17] for electrostatic waves propagating along the magnetic field, in a plasma of equal ion and electron temperatures.

The first interpretation of this phenomenon was given by Rosenbluth [18]. He predicted, on the basis of Vlasov's collisionless equation, ion electrostatic waves with (a) frequency somewhat in excess of the ion cyclotron frequency, (b) propagation at large angles with the magnetic field. Furthermore, the waves are excited if the electron drift velocity exceeds ~10 $v_{i\ th}$, and the fastest growing ones are those for which $K_{\perp}R_L \sim 1$, $\omega \approx 1.2\ \omega_{ci}$. A simpler treatment, based on the Boltzmann moment equations, was given later [14].

In a second experiment, by D'Angelo and Motley [19], low-frequency oscillations (in the 10 to 30 kc/sec range) were observed in both Cs and K plasmas, when an ion sheath was present at the hot tungsten plate which ionized Cs or K. The frequencies of the oscillations fell into three groups: 9 to 12 kc/sec, 17 to 20 kc/sec, and 26 to 29 kc/sec, i.e. they were, roughly, in the ratio 1 : 2 : 3 . In each frequency range no magnetic field dependence of the frequency was observed, for values of B between ~2000 and ~5000 gauss. From measurements of the relative phases of the oscillations at different locations in the plasma column, the picture emerged of a density perturbation travelling azimuthally, with a single maximum (m = 1) for the first range of frequencies, a double maximum (m = 2) for the second range, and a triple maximum (m = 3) for the third. The velocity of azimuthal propagation of the disturbance was the same in the three cases. The oscillations were interpreted [20] as low-frequency ion waves propagating perpendicular to both the applied magnetic field and the existing density gradients. Due to the low value of the β (ratio of material to magnetic pressure) of this plasma ($\beta \approx 10^{-7}$) the waves are essentially quasi-electrostatic waves. The E vector is parallel to the K vector, both being perpendicular to the applied B field. With no steady radial electric fields existing in the plasma column, the ions in the zero-order motion have a macroscopic velocity in the azimuthal direction determined only by the density gradient. The phase velocity of the waves coincides with this macroscopic velocity of the ions. The dispersion relation obtained in reference (20) is the same as that given by Frieman and Greene [21], from the Vlasov equation.

In a third experiment, by Wong, D'Angelo and Motley [22], ion electrostatic waves propagating along the magnetic lines of force were excited by means of a grid oriented perpendicular to the axis of the plasma column. An oscillatory voltage was applied to the grid, which was biased to collect ion current. A similar grid, also biased negatively and located perpendicular to the axis of the column, detected oscillations in the ion current. The second grid could be moved along the magnetic lines and a measurement was possible of the phase velocity of the waves and of their attenuation length δ. The results of the measurements are given in Figs. 4 and 5. A comparison between the experimental results and a collisionless theory of ion waves by Fried and Gould (23) gave the following results:

1) Phase velocities of 1.3×10^5 cm/sec were measured for cesium and 2.5×10^5 cm/sec for potassium, independent of the plasma density in the range

$$3 \times 10^{10} \text{ cm}^{-3} < n < 3 \times 10^{11} \text{ cm}^{-3}$$

and with no measurable dispersion. The ratio

$$v_{ph}(K)/v_{ph}(Cs)$$

was found to be about 1.9. All these results are in quite close agreement with theory, except for the absolute values of the phase velocities, both in Cs and K, which are perhaps somewhat (30 to 40 %) in excess of the theoretical values. Further refinement of the experimental methods might reduce these discrepancies.

2) The damping of the waves is very strong and can apparently be accounted for only in terms of collisionless (Landau) damping. It is interesting to note that, owing to the condition $T_e \approx T_i$ prevailing in these plasmas, the expected Landau damping is so large that the waves had been classified by Fried and Gould as "unobservable". Again, the fact that they could be observed must be attributed almost entirely to the "quiescence" of the plasmas in which the experiments were performed.

c) Spectroscopy experiments

So far, alkali-metal plasmas have not been a very fruitful source of spectroscopy experiments. Because of the mechanism of production of Cs and K plasmas and the very low (0.2 eV) electron temperature, the light of interest coming from the plasma column is due to recombination of ions and electrons. A measurement of the recombination coefficient of cesium was attempted by Hofmann, Hinnov, Hirschberg, and D'Angelo [24], by measuring the amount of light emitted in $6^2P \rightarrow 6^2S$ and $4^2F \rightarrow 5^2D$ transitions (see Fig. 6). The measurements were made with a half-meter Ebert type monochromator, equipped with a liquid nitrogen cooled infrared sensitive photomultiplier. The detection system was calibrated for absolute intensity measurements against a standard tungsten ribbon lamp. Assuming that the intensity of the resonance lines ($6^2P \rightarrow 6^2S$) arises entirely by radiative cascading due to recombination, yields a recombination coefficient of $\sim 3 \times 10^{-11}$ $cm^3 sec^{-1}$. This is an overestimate, because a major contribution to the resonance lines appears to be resonant scattering of the light from the hot tungsten plates. A somewhat more reliable result might be expected from the measurement of the $4^2F \rightarrow 5^2D$ light. Adding - somewhat arbitrarily - a comparable contribution from all other transitions (i.e. cascade paths that avoid the 4F level), one gets a value of ~ 3 to 4×10^{-12} $cm^3 sec^{-1}$. The result is not in disagreement with the calculated recombination coefficient from electron-electron-ion [25], [26] collisions, for a temperature $kT \approx 0.2$ eV and an ion density $n \approx 5 \times 10^{11}$ cm^{-3}. It should be noted here that recent measurements by Knechtli and Wada [27] of the recombination coefficient in cesium seem to give values of α in fair agreement with the spectroscopic determination. However, the magnitude of α remains to some extent still an open question [6].

d) Beam-plasma interaction experiment

An experiment on the amplification of a microwave signal on an electron beam which passes through a 2.2 cm length of cesium plasma was conducted at Stanford, by Allen and Kino [28]. The electron beam passes through a helix on which a microwave signal is applied. After modulation, the beam goes through the cesium plasma and an output signal is detected on a second helix. Fig. 7, from Allen and Kino [28], shows the measured gain as a function of the frequency of the applied signal. The solid line is a theoretical curve calculated for a beam current of 3.5 ma. Gain is obtained approximately between ω_c and $(\omega_p^2 + \omega_c^2)^{1/2}$, where ω_c is the electron cyclotron frequency for the applied field, and ω_p the plasma frequency.

IV. Possible further experiments with alkali-metal plasma devices

This last section contains a few considerations about experiments which appear feasible with alkali-metal plasma devices. Obviously, such considerations can be expected to cover but a small portion of future experiments. At the same time they might be subject to the main drawback of most predictions. Still, a few words on possible future developments might not be entirely out of place here.

The wave excitation and propagation experiments of section III.b) were all conducted in plasmas with approximately equal ion and electron temperatures. It will be of interest to extend the experiments to plasmas with $T_e \gg T_i$. In this connection one can heat the electrons either by simply passing a current through the plasma column or by absorption of microwave power at the cyclotron frequency of the electrons. Perhaps, because of the short energy exchange time between electrons and ions in the alkali-metal plasmas, compared with recombination times, it will be necessary in either case to use a pulse technique for heating the electrons and perform the experiments in the time available before appreciable heating of the ions by collisions with the electrons occurs. Also of importance might be the observation of a decrease of the Landau damping of low-frequency ion waves of section III.b), when T_e/T_i is made much larger than unity.

For $T_i = T_e \approx 0.2$ eV, at densities of the order of 10^{12} cm^{-3} or larger, one should be able to observe a transition from Landau damping to viscous damping (ion-ion collisions) of ion acoustic waves. An experiment of this kind is under way in Princeton [29].

With devices suitably designed, it is possible to introduce in the alkali-metal plasma columns relatively large amounts of a neutral inert gas (like A, etc.) and study the effect on the attenuation of ion waves of collisions of the alkali ions with the atoms of the inert gas.

Of interest will be also the use of alkali-metal plasmas in geometries with curved magnetic fields, like the stellarators.

Beside providing information on particle drifts due to the curvature in the magnetic lines ($\underline{B} \times \nabla \underline{B}$ drift and centrifugal drift), such experiments might perhaps be able to throw some light on the relation between the short "pump-out" times observed in stellarators and the passage of current through the plasmas. Furthermore, because of the condition $T_i = T_e$ prevailing in the alkali-metal plasmas, the strong (Landau) damping of the ion acoustic waves of section III.b) is expected to reduce a possible effect of ion wave instabilities on plasma confinement .

An actual experiment along these lines is being performed at Max-Planck-Institut in Munich.

Acknowledgements

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Fig. 1

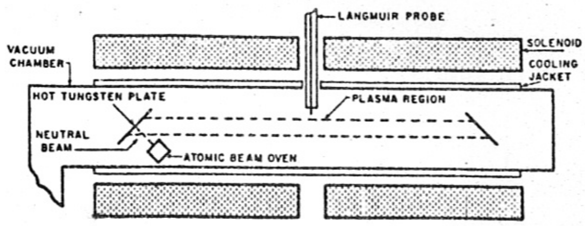


Fig. 2

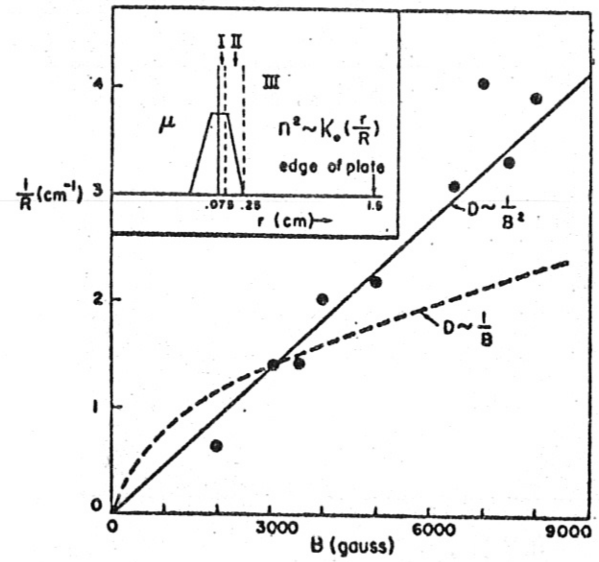
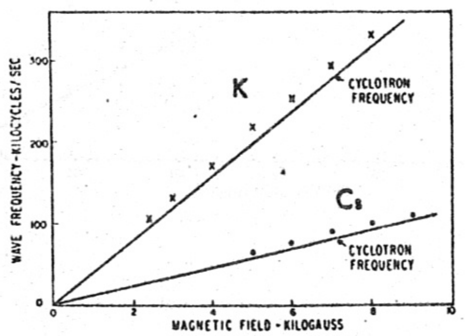


Fig. 3



(Captions: see p. 16)

Fig. 4

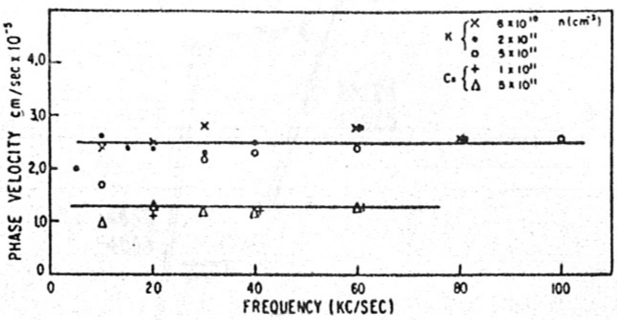
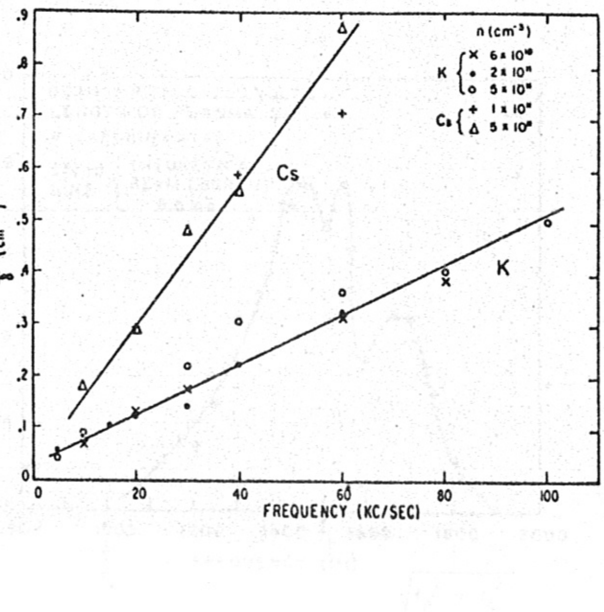


Fig. 5



(Captions: see p. 16)

Fig. 6

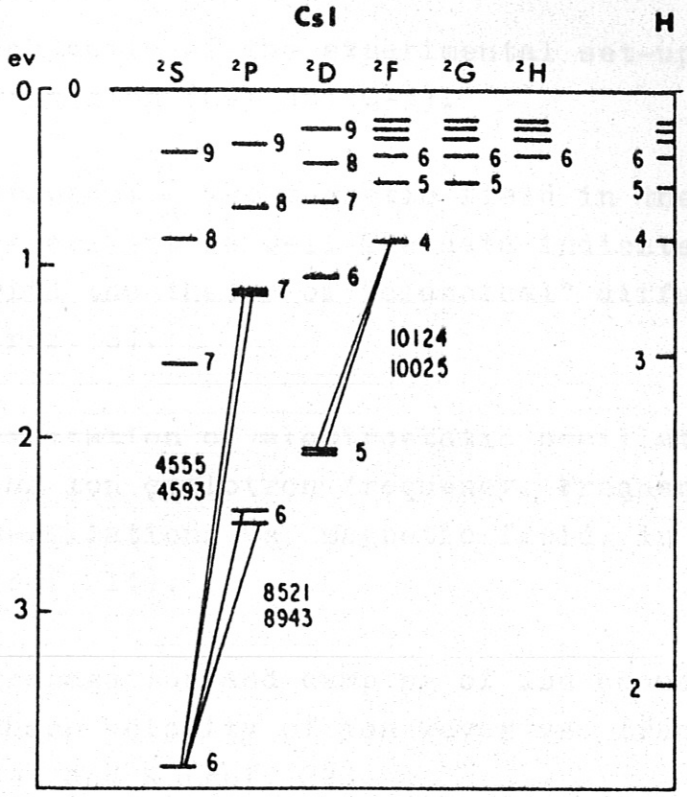
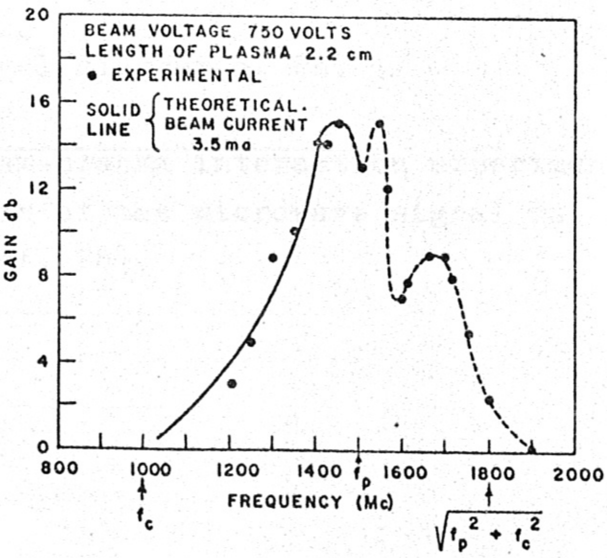


Fig. 7



(Captions: see p. 16)

Figure Captions

Fig. 1 Schematic of the experimental set-up in use at Princeton (Q-1 and Q-3).

Fig. 2 Graph of $\frac{1}{R}$ vs. magnetic field in the diffusion experiment in Q-1. The data indicate agreement with the theory of "classical" diffusion (ref. 6).

Fig. 3 Excitation of electrostatic oscillations near the ion cyclotron frequency. Frequency of the oscillations vs. magnetic field, in Cs and K (ref. 14).

Fig. 4 Propagation and damping of ion acoustic waves. Phase velocity of ion waves vs. frequency, in Cs and K (ref. 22).

Fig. 5 Propagation and damping of ion acoustic waves. $1/\delta$ vs. frequency, in Cs and K. δ = attenuation length (ref. 22).

Fig. 6 Level diagram of Cs.

Fig. 7 Beam-plasma interaction experiment. Measured gain of the microwave signal vs. frequency (ref. 28).

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