NOAA TM ERL AL-5



# NOAA Technical Memorandum ERL AL-5

**U.S. DEPARTMENT OF COMMERCE**
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

## Laboratory Investigations of Driven Low Frequency Plasma Oscillations

EDWARD J. YADLOWSKY
PAUL D. GOLDAN



Aeronomy Laboratory
BOULDER, COLORADO
January 1973

# NMENTAL RESEARCH LABORATORIES

## AERONOMY LABORATORY







NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Technical Memorandum ERL AL-5

# LABORATORY INVESTIGATIONS OF DRIVEN LOW FREQUENCY PLASMA OSCILLATIONS

Edward J. Yadlowsky
Paul D. Goldan

Prepared for the U. S. Atomic Energy Commission
Under Contract No. AT(49-8)-3006



Aeronomy Laboratory
Boulder, Colorado
January 1973

TABLE OF CONTENTS

# LABORATORY INVESTIGATIONS OF DRIVEN LOW FREQUENCY PLASMA OSCILLATIONS

Edward J. Yadlowsky and Paul D. Goldan

## 1. INTRODUCTION

The work described in this report is directed toward exciting and identifying the parametric decay instability in an unmagnetized plasma. In the course of this work, we have found that low frequency oscillations can be excited by applying rf potentials in conjunction with dc potentials to grids immersed in the plasma, in addition to the well-known oscillations excited with dc potentials alone. Some of the low frequency oscillations that we have excited exhibit the characteristics of ion-acoustic waves associated with excitation of the parametric decay instability; however, the characteristics of all the oscillations reported in this work are similar and are thought to be the same phenomenon excited by different techniques. The report is divided into an experimental section followed by three sections that discuss the three general catagories of low frequency oscillations that have been excited in an unmagnetized plasma.

## 2. EXPERIMENTAL SET-UP

The work was carried out in a low pressure argon discharge, shown schematically in figure 1. The plasma was generated in a metal discharge tube which served as an anode, and typical plasma parameters are: argon pressure $\sim .5$ mm torr, electron density $n_e \sim 10^8/cm^3$, electron temperature $T_e \sim .5eV$, and $T_e >> T_i$. The oscillations were excited by applying dc or ac voltages or both to the two transparent grids inserted into the plasma. The plane of the two grids is oriented perpendicular to the tube axis and the grids can be moved individually or together along tube axis. This configuration was chosen because it provides a simple plane geometry for comparison with theoretical predictions and it is directly amenable to investigation with the electron beam probe, one of our principle diagnostic tools. The electron beam passes through the holes in the metal discharge tube perpendicular to the tube axis (see figure 1). The axial electric fields within the plasma can be inferred from the lateral deflections of the electron beam from an equilibrium position. Details of how the beam deflections are measured and calibrated are supplied in Goldan and Yadlowsky (1971). The high spatial resolution and non-perturbing nature of the beam make it an ideal tool for measuring the ac and dc electric fields throughout the region between the grids, especially in the sheaths. The electric field can then be spatially integrated to obtain a potential distribution. As a check on this procedure, the space potential in the quiescent plasmas, as measured with a Langmuir probe, was compared with the value obtained by this technique and was found to be in good agreement. The importance of these measurements in determining instability criteria and evaluating boundary effects is discussed in the next section.

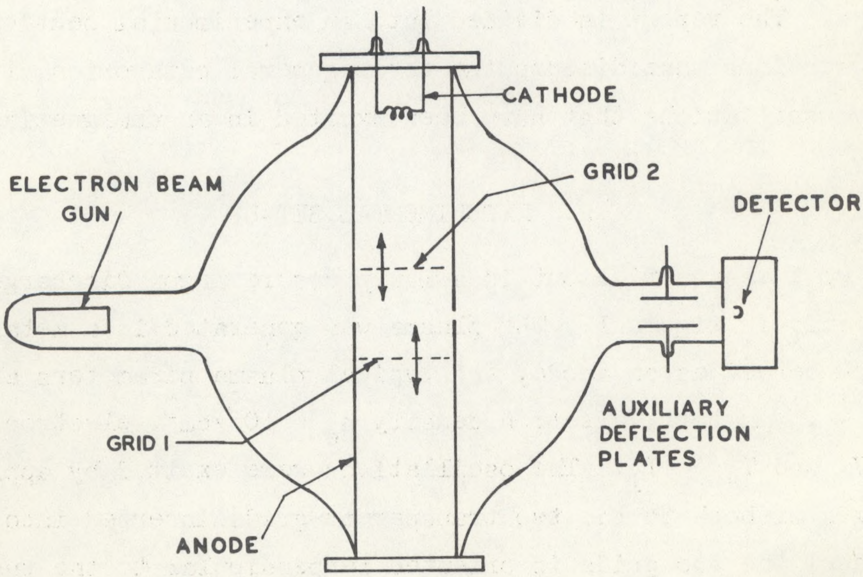


Figure 1. Schematic diagram of experimental apparatus. Grids 1 and 2 can be moved along the axis of a 9 cm dia. metal tube which served as the anode.

Low frequency oscillations have been excited in this system by applying dc potentials alone or in combination with rf potentials to the grids. The frequency spectrum of these oscillations exhibits many of the properties associated with standing waves in a resonant cavity. The dc excited oscillations are of interest in this program because we can study the nature of low frequency oscillation in an inhomogeneous plasma without the complications of an external rf field. The effect of boundaries on these oscillations can be evaluated from these studies. The salient features of these oscillations and how we think they relate to the problem of identifying the parametric decay instability are described in the next section.

## 3. OSCILLATIONS EXCITED BY DC POTENTIALS

Oscillations in the frequency range of 10 to 150 kHz have been excited when appropriate dc voltages have been applied to the grids. The threshold requirement is that the potential on grid 1 be about 2 to 4 v positive with respect to grid 2. The Fourier spectrum of the oscillations consists of equally spaced harmonics. The frequency of the fundamental is observed to be inversely proportional to the spacing between the grids (see figure 2). We measured the potential distribution between the grids because we wanted to see if there were any obvious changes as the potential on grid 1 was raised from below threshold (see figure 3) to above threshold (see figure 4). The fluctuating electric field associated with the instability was measured with a narrow band voltmeter tuned to the fundamental and the spatial distribution of the field is shown in figure 5.

The characteristics of these oscillations resemble sound waves excited on a string, and one is tempted to identify them as current excited ion acoustic waves. However, oscillations with characteristics similar to those described above have been observed in therimonic converters (see Luke and Jamerson, 1961) in Q devices (Buchel'nikova and Salimov, 1966) and in low pressure discharge tubes similar to ours (Tanaka et al., 1967). It is evident from the explanations which have been discussed in the literature that the excitation mechanism is not very well understood

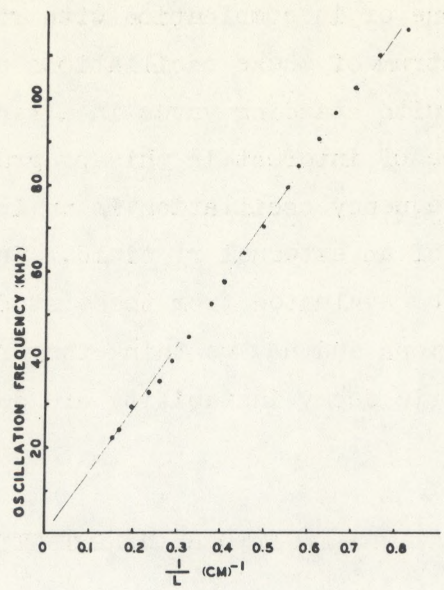


Figure 2. Frequency of the oscillation excited by applying dc potentials to grids 1 and 2 as a function of $L^{-1}$ where L is the intergrid spacing.

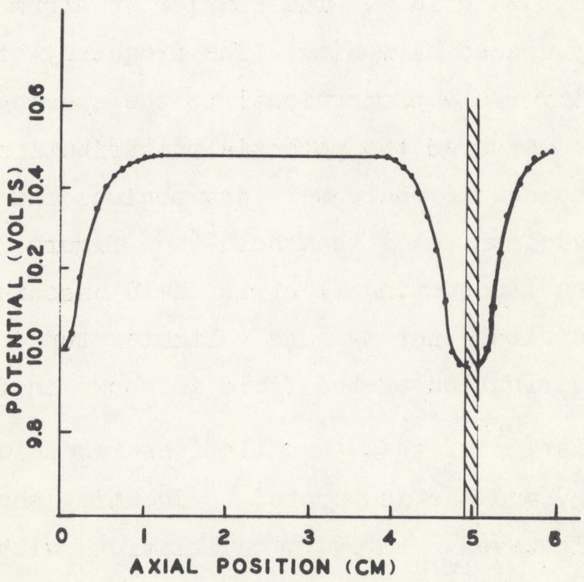


Figure 3. Space potential as a function of the distance from grid 1 when the potential applied to the two grids is 10 v. The position of grid 2 is designated by the cross hatched area. The space potential measured with a Langmuir probe for the same conditions but on a different day was 10.7 v.

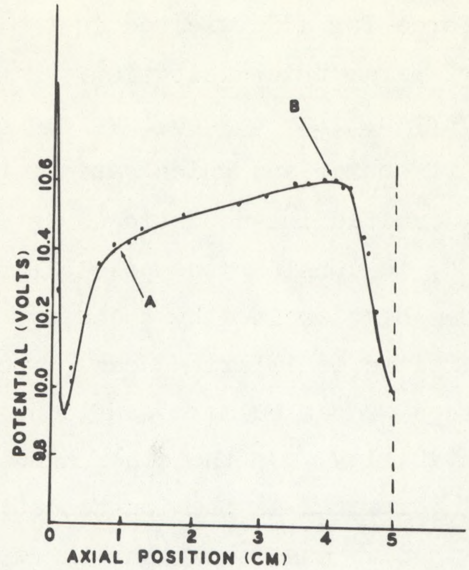


Figure 4. Space potential as a function of the distance from grid 1 when the potential applied to grid 1 was 12.5 v and to grid 2 was 10.0 v. The position of grid 2 is designated by the dashed line.

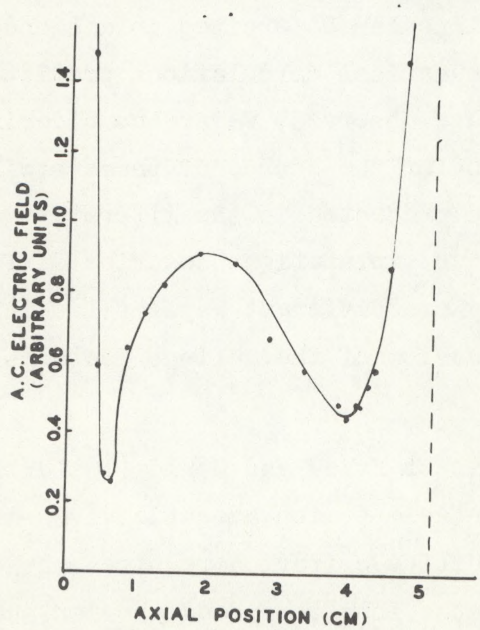


Figure 5. AC electric field amplitude of the low frequency oscillations as a function of the distance from grid 1. The position of grid 2 is designated by the dashed line. The dc conditions are the same as in figure 4.

(Buchel'nikova and Salimov, 1966, 1968; Tanaka et al., 1967; Burger, 1965). In general the driving force for a dc excited instability would not be of interest to a study of rf parametric excitation. However, in our system these oscillations are very similar to the low frequency oscillations which we have excited with an rf source and which satisfy the theoretical requirements for parametrically excited ion-acoustic waves. Because of the similarity, we were forced to consider the possibility that the same oscillation phenomenon has been excited by these two different driving techniques. If the dc excited oscillations can be positively identified as ion-acoustic waves, then we can be more confident that we have excited the parametric decay instability. On the other hand, if the dc excited oscillations cannot be interpreted as the ion-acoustic waves predicted by Fried and Gould (1961), then we must show that there is a difference between the low frequency oscillations excited by the two techniques before we can establish that the rf pump has excited the parametric decay instability. Burger (1965) presents a numerical analysis that shows relaxation oscillations can be excited in a bounded plasma system such as ours. Since his numerical calculations predict qualitatively many of the features we have observed, we are considering his analysis as an alternative explanation for the source of these oscillations; however, we think that the analyses presented in the literature are insufficient to determine whether the two explanations describe different excitation mechanisms or whether they are different ways of looking at the same phenomenon. A brief discussion of the salient features of these theoretical explanations follows.

The stability analysis of Fried and Gould (1961) shows a uniform unmagnetized plasma is unstable to ion-acoustic waves if a current flows in the plasma. The instability criterion requires the drift velocity, u, of the electrons relative to the ions to exceed the ion-acoustic phase velocity, $c_s$, when $T_e \gg T_i$.

The oscillations satisfy the dispersion relation

$$\omega = \frac{c_s k}{(1 + (k/k_D)^2)^{\frac{1}{2}}} , \qquad (1)$$

which reduces to $\omega = c_s k$ when $k \ll k_D$. The symbols are defined by $k_D = (n_e^2/KT_e)^{\frac{1}{2}}$ and $c_s = (KT_e/m_i)^{\frac{1}{2}}$. The physical meaning of the criterion $u > c_s$ is that there are more electrons moving faster than the wave than there are moving slower, and the wave particle interactions increases the wave energy. Figure 4 indicates that our measurements are consistent with the instability criterion, since oscillations are observed only when the potential difference indicated by the points A and B exceed 0.1 to 0.2 v, which is more than the potential difference required to accelerate the electrons to the ion-acoustic phase velocity. To explain the observed frequency dependence on inverse grid spacing, one must postulate the existence of ion wave reflections at the grids. The reflections give rise to a standing wave between the grids, and the system behaves like a resonant cavity. (Figure 5 can be interpreted as representing a standing wave pattern.) We must point out that the reflection of ion waves is not well understood, and additional theoretical work must be done before we can ascertain the full merits of this model.

Burger (1965) used a numerical simulation technique to calculate the current through a thermionic diode for a range of electrode voltages and cathode ion and electron emission characteristics. His calculations predict oscillations whose general character is very similar to oscillations observed both in the diodes he attempted to model and in our experiment. Burger explained the existence of these oscillations on the basis of the following physical argument: because of the very large difference in mass between the ions and electrons, the electrons are free to redistribute themselves spatially in times so short that the ions appear relatively fixed. Recognizing this fact, Burger states that the "steady state" solution for the thermionic diode is not stable against electron redistribution for some particular range of diode operating parameters.

The electrons being free to move, do so, leading of course to the collapse of the assumed ion spatial distribution but on a time scale comparable to an ion transit time across the diode. The ion-electron system is then again driven toward the "steady state" distribution and the whole cycle repeats, leading to a periodic distrubance.

Burger's analysis is insufficient to determine whether this is a different instability mechanism or whether he has described the nonlinear limit of the ion-acoustic instability of Fried and Gould (1961).

## 4. OSCILLATION EXCITED BY RF PUMP FREQUENCY $f_o (f_{pi} \ll f_o < f_{pe})$

An rf voltage frequency $f_o$ was applied to grid 2 in an attempt to excite the parametric decay instability; however, low frequency oscillations were excited when the driving voltage exceeded a threshold value for a wide range of driving frequencies from 10 to 50 MHz, which is well above the ion plasma frequency ($f_{pi} \simeq 500$ kHz) and well below the electron plasma frequency ($f_{pe} \simeq 90$ MHz). The 10 MHz is a lower limit imposed by the capability of the rf generator used. The oscillation excited in this fashion have the same characteristics as the oscillation excited with dc potentials. The frequencies in both cases are approximately the same and are inversely proportional to the grid spacing. The frequency of the rf excited oscillations depend weakly on the rf voltage. Oscillations have been excited by a similar technique in Q devices and are reported by Demirklianov et al. (1967). The theoretical explanations for these oscillations indicate that the excitation mechanism is not well understood (see Demirklianov et al., 1971). We think that the broad range of exciting frequencies coupled with observations described below exclude the possibility of parametric excitation. We have some experimental indications that rectification effects in sheaths around the grids can alter the time average of the potential distribution in the plasma. We think that it might be possible for the time averaged potential between the grids in the presence of the rf field to be similar to the potential distribution which is present, when dc potentials alone are used to excite the instability. Before we can understand how the oscillations are excited we must determine to what extent the rf field alters the integrid potential distribution.

## 5. OSCILLATION EXCITED BY RF PUMP AT FREQUENCY $f_o (f_o \sim f_{pe})$

After extensive searching, preliminary results indicate that we have excited oscillations whose characteristics strongly resemble those predicted for the parametric decay instability (see DuBois and Goldman, 1967). The parametric excitation that we are concerned with may be viewed as the excitation of an ion wave at frequency $\omega_i$ with a wave number $k_i$ and of an electron wave at frequency $\omega_e$ with a wave number $k_e$ by an externally impressed electric field, $E_o \cos \omega_o t$. Oscillations are excited when the frequency matching condition $\omega_o \simeq \omega_e + \omega_i$ ; the wave number matching condition $k_o \simeq k_e + k_i$ are satisfied, and the magnitude of the driving field exceeds a threshold value. The frequencies $\omega_i$ and $\omega_e$ are given by (1) and (2), respectively:

$$\omega_e = (\omega_{pe}^2 + 3V_t^2 k^2)^{\frac{1}{2}} \qquad (2)$$

where $V_t = \sqrt{KT_e/m_e}$.

Experimentally we observe that a low frequency oscillation of frequency $f_i$ and a high frequency oscillation of frequency $f_2$ is excited in the plasma when the frequency of the driving voltage $f_o$ is in the range of 105 to 115 MHz, and the magnitude of the driving voltage exceeds a threshold value. For these plasma conditions the plasma frequency calculated from Langmuir probe measurements of the density is about 90 MHz. The magnitude of the threshold electric field has not yet been measured, but the frequency matching condition $f_o = f_1 + f_2$ has been verified. Since the ion-acoustic frequency given by (1) is much less than the electron plasma frequency and $k V_T \ll \omega_{pe}$, the frequency matching condition reduces to $\omega_o \simeq \omega_{pe}$. Although the observed pump frequencies (105-115 MHz) are somewhat larger than the calculated value (90 MHz), we have observed that the optimal pump frequency is roughly proportional to the square root of the arc current. Since the arc current is proportional to the number density, we feel that the observations are qualitatively in agreement with the predictions of theory.

The preliminary observations made to date indicate that the low frequency oscillations excited in this fashion are very similar to the oscillations excited with dc potentials. In both cases the oscillation frequencies are within a factor 2 of one another. A more important similarity is the observation that the oscillations in both cases appear to be excited in a resonant cavity defined by the grids. The dependence of the oscillation frequency on the grid spacing for the dc excited instability was already discussed in Section 3.

The following observations associated with the parametrically excited oscillation are an even stronger example of the importance of system boundary conditions. We have observed that the amplitude of the system response at the ion-acoustic frequency excited is strongly dependent on not only the RF pump frequency but also upon the intergrid spacing. For any given intergrid spacing, the amplitude of the low frequency wave excited may be maximized by appropriately tuning the pump frequency. If the intergrid spacing is now altered, the amplitude of the low frequency wave will decrease, and the spectrum will broaden but still remain centered about the same frequency. One can now retune the RF pump frequency to again optimize the amplitude of the low frequency response by raising it if the intergrid space has been shortened, and, lowering it if the spacing has been lengthened. The center frequency of the excited low frequency oscillations will change in the same direction as the RF pump frequency. The behavior can be readily understood if one assumes that the grids act as boundaries of a cavity where resonant frequencies are inversely proportional to the intergrid spacing. To obtain a maximum response, there are now two frequency matching conditions that must be satisfied. To excite the oscillation, the parametric pumping condition ($\omega_o \approx \omega_i + \omega_e$) must be satisfied and also $\omega_i$ must be near one of the cavity resonant frequencies. If the grid spacing is altered, then the cavity will be driven off resonance and the response will decrease but the frequency will remain at $\omega_i$ as determined by the parametric pumping relationship. We feel that the simularities between the oscillations excited by dc and rf potentials indicates that the same oscillation phenomenon has been excited by the two techniques. This implies that the effects of boundaries can be studied using the dc excitation scheme without the complications associated with the impressed rf field and the results can be applied to the analysis of parametric excitation in a bounded system.

## 6. ACKNOWLEDGMENTS

This work was supported in part by the U. S. Atomic Energy Commission Contract No. AT(49-8)-3006.

## 7. REFERENCES


1. Buchel'nikova, N. W. and R. A. Salinov (1966), Excitation of Ionic Sound Waves in Potassium and Cesium Plasma, Teplofizika Vysokikli Temperatur 4: 27 (Soviet Phys.-High Temp. 4: 23, 1966).
2. Buchel'nikova, N. W. and R. A. Salimov (1969), Turbulent Diffusion and Heating in the Current Driven Instability, Zh. Teor. Fiz 56: 1108 (Soviet Phys. JETP 29: 595, 1969).
3. Burger, P. (1965), Theory of Large-Amplitude Oscillations in the One-Dimensional Low-Pressure Cesium Thermionic Converter, J. Appl. Phys. 36: 1938.
4. Demirkhanov, R. A., G. L. Khorasanov, and I. K. Sidorova (1967), Thermal Cesium Plasma in a Strong High-Frequency Electric Field, Zh. ETF Pis. Red 6: 861 (JETP Letters 6: 300, 1967).
5. Demirkhanov, R. A., G. L. Khorasanov, and I. K. Sidorova (1971), Resonance Phenomena in an Alkali Plasma Situated in an Alternating Electric Field, Zh. Eksp. Teor. Fiz 59: 1873 (Soviet Phys. JETP 32: 1013, 1971).
6. DuBois, D. F. and M. V. Goldman (1967), Parametrically Excited Plasma Fluctuations, Phys. Rev. 164: 207.
7. Fried, B. D. and R. W. Gould (1961), Longitudinal Ion Oscillations in a Hot Plasma, Phys. of Fluids 4: 139.
8. Goldan, P. D. and E. J. Yadlowsky (1971), Plasma Resonance and Standing Longitudinal Electron Waves, Phys. of Fluids 14: 1990.
9. Luke, K. P. and F. E. Jamerson (1961), Low Frequency Oscillations in a Filamentary Cathode Cesium Diode Converter, J. Appl. Phys. 32: 321.
10. Tanaca, H., A. Hirose, and M. Koganei (1967), Ion-Wave Instabilities in Mercury-Vapor Plasma, Phys. Rev. 161: 94.