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RF OSCILLATIONS AND POWER OUTPUT IN ALKALINE THERMIONIC CONVERTERS

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UAC - 6389
for Haystack D. Young

I. INTRODUCTION

Plasma oscillations in cesium, rubidium, and potassium cells have been described in several publications.⁽²⁻⁹⁾ The first basic treatment was already given by Tonks and Langmuir⁽¹⁾ and recently by Zollwig and Gottlieb⁽⁶⁾, Birdsall and Bridges⁽⁷⁾, Eichenbaum and Hernquist⁽⁹⁾ and other authors.

The frequencies of plasma ion oscillations are usually in the order of several hundred kc up to one mc and are functions of the ion density, electron density, atomic weight, and distance between the emitter and collector.⁽⁵⁻⁹⁾

The following pages will report experiments using a potassium plasma cell with a tantalum emitter and a silver-plated copper collector. The rf frequencies, rms voltages, power output and other quantities were measured under various conditions of emitter temperature, potassium vapor pressure, dc and rf loads.

II. EXPERIMENTAL PROCEDURE

Figure 1 shows the experimental arrangement in its general features, leaving out details.

The upper portion consisted of the electron gun and a tantalum emitter of 0.5 in. diameter and the tantalum diaphragm as seen in Fig. 1. The emitter was kept at ground potential. Opposite to the emitter at a distance of 2.2 mm was the collector surrounded by a guard ring. Both the collector and guard ring were oil cooled. The collector area was 0.317 cm^2 . The space between emitter and tantalum disc on the one side and the collector-guard ring combination at the other one was filled with potassium vapor. The vapor pressure was regulated by

the controlled temperature of a potassium cold trap. The electron gun section and the cell were evacuated by a vacuum pump. The collector and guard ring were connected with an X-Y recorder that traced in a few seconds the voltage current characteristics of the cell. A voltage varying continuously from -4 to +6 V against the grounded emitter was applied to the collector and guard ring from a transistorized dc reversing circuit.⁽⁸⁾ The rf choke, CH_1 , between the collector and the dc reversing network excluded rf current. Another rf choke, CH_2 , prevented the flow of rf current into the recorder. A capacitance, C , of $2\mu F$ separated the rf from dc. The rf section was connected to an oscilloscope and a vacuum tube voltmeter, VTV, reading rms volt. The rf voltage could be observed and measured at open circuit and varying load conditions, or could be short circuited as seen in Fig. 1.

The resistance, R_1 , shown in series with CH_1 includes the rf choke resistance and determined the dc current scale for the characteristic.

While the dc characteristics could be traced continuously, the rf frequencies and voltages were recorded at the following dc positions: +3V, +1V, zero V, -1V and -2V, with rf open circuit.

The dc characteristics were traced, whenever possible, with an rf open circuit, marked by o and rf short circuit, marked s for identical emitter temperature and potassium pressure.

If no definite rf frequency could be established, but the voltmeter showed an rf voltage, rf noise was recorded.

While the fundamental frequencies are always shown, the wave shape was frequently very far from sinusoidal, as seen in Fig. 10.

The last column shows the dc open circuit voltages, "OP-C-DC-V".

III. EXPERIMENTAL RESULTS

The results are recorded in graphs and tables below. The tables show the measured and calculated values from column 2-11 or 12. Columns 2 and 3 refer to the potassium pressure and atoms/cc in the cold trap. These densities are not identical with the actual atomic concentration in the cell due to the higher temperature between emitter and collector. Columns 5-9 show the rms voltage of the rf for different dc voltages at the collector; columns 10 and 11 refer to the dc and rf power maxima. The dc maxima result directly from the current voltage product at the knee of the characteristics in Fig. 2-9, usually at about -2 to -2.5 volt. The rf maxima were obtained by inserting different inductance free resistances into the rf section between capacitance, C, and ground, and the largest value of V^2/R were recorded. The rf frequencies are shown directly on the curve of the characteristics.

In addition to the rf frequencies, a low frequency noise was observed simultaneously with the rf. The ^{emitter} temperatures were usually so high, $T > 1900^\circ\text{K}$, that no potassium layer existed on its surface.

During a series of experiments, the potassium vapor pressure was kept nearly constant, while the emitter temperature was increased from an initial value from one curve to the next one. The curves for each characteristic was marked, a,b,c, etc. The scale to be used for the current readings is indicated with a multiplication factor 1 or 10. The curve marked with o refers to rf open and the one with s to rf short circuit.

The series of curves shown in Fig. 2 with details given in Table 1 have a very low potassium vapor pressure. The portion at the right side of the zero voltage is not usable for conversion, since energy is fed into the cell, but gives important information. The position of the rfpm did not coincide with the dcpm, but was usually close to dc short circuit, i.e., zero volt.

Table 1

POTASSIUM CELL

1	2	3	4	5	6	7	8	9	10	11	12
	P(K) mm Hg	No(K) AT/cc	T _e °K	AT + 3 V _c RMS-V	AT + 1 V _c RMS-V	AT-0-V _c RMS-V	AT-1- V _c RMS-V	AT-2 V _c RMS-V	PM DC	PM RF	OP-C DC-V
a	2.2 x 10 ⁻⁴	5.4 x 10 ¹²	1950	---	---	---	---	---	2 mw	---	3.2
b	2.1 x 10 ⁻⁴	4.8 x 10 ¹²	2030	0.26	0.37	0.46	0.48	0.37	7.4 mw	0.3 mw	3.4
c	2 x 10 ⁻⁴	4 x 10 ¹²	2170	1.8	2.7	2.3	1.75	0.9	36 mw	3.5 mw	3.6
d	1 x 10 ⁻⁴	3.9 x 10 ¹²	2300	6.0	4.9	3.2	2.3	1.0	143 mw	36 mw	3.7

As is seen, curve a shows no rf oscillations.

In curve b-o the rf frequencies decrease with a decreasing dc collector voltage. The left side of the curve o has a hump with a negative portion of the characteristic. The rfpm in b is about 4% of the dcpm (Table 1). The s curves do not show the hump or a negative characteristic.

Curve c shows the same general features as to frequency dependence. The negative characteristic of the curve and the hump are much more pronounced in c. Very distinct becomes the difference of the dc current between o and s. At the knee of the curves, at about -2.6 V, the two curves coincide and the oscillations discontinue at this point. The rfpm reaches 10% of the dcpm. In d the same features are repeated, but are still more pronounced. At zero volt (short circuit), the o current is only 54% of the s current, while the rfpm increases to 25% of the dcpm. Comparing for the same dc voltage, the frequencies decrease with increasing emitter temperatures and electron densities at essentially constant vapor pressure. This agrees with theoretical calculations.^(1,5,7)

Figure 3 and Table 2 show the results for higher temperatures. Table 2 does not show the RMS V, since these values are given in Fig. 3. Fig. 6a, b, c, d, show the frequency variations as a function of applied dc voltage.

Table 2

POTASSIUM CELL

2	3	4	5	6	7
P(K) mm Hg	No(K) AT/cc	T _e °K	PM DC	PM RF	OP-C DC-V
2.2×10^{-4}	4.5×10^{12}	2380	288 mw	65 mw	3.8
2.2×10^{-4}	4.5×10^{12}	2520	1.1 W	50 mw	3.7

Figure 3 a is similar to 2d with the rfpm about 22% of the dcpm. In 3b this ratio is only 5%. Another group of curves for a higher potassium pressure is shown in Fig. 4 with Table 3 and Fig. 5 with Table 4.

Table 3

POTASSIUM CELL

1	2	3	4	5	6	7	8	9	10	11
	P(K) mm Hg	No(K) AT/cc	T _e °K	AT + 3 Vc RMS-V	AT + 1 Vc RMS-V	AT-O-Vc RMS-V	AT-1 Vc RMS-V	AT-2 Vc RMS-V	PM DC	PM DC
a	3.7×10^{-4}	9×10^{12}	2040	0.22	0.27	0.41	0.41	0.41	6.3 mw	0.048 mw
b	4.5×10^{-4}	10^{13}	2250	1.1	1.15	1.4	1.4	0.7	35 mw	0.49 mw
c	4.5×10^{-4}	10^{13}	2375	6.5	4.5	3.4	2.4	---	260 mw	60 mw

In Fig. 4, the oscillations start at higher temperatures and electron pressures. The general features are similar as before.

The effect of potassium vapor pressure can be observed by comparing 2b with 4a and 2c with 4b. The temperatures are approximately equal, but the vapor pressures vary. It appears that the frequency increases somewhat with the vapor pressure in agreement with the theories.

Table 4 refers to Fig. 5 and shows that the ratio of rfpm to dcpm is about 22% for Fig. 5a, but about zero for 5b.

At potassium pressures above 10^{-2} mm Hg, the rf noise becomes predominant and the frequencies cannot be observed anymore. Also, the rf power decreases and the o and s curves coincide practically.

Table 4
POTASSIUM CELL

1	2	3	4	5	6	7	8	9	10	11
	P(K) mm Hg	No(K) AT/cc	T _e °K	AT + 3 Vc RMS-V	AT + 1 Vc RMS-V	AT-0-Vc RMS-V	AT-1 Vc RMS-V	AT-2 Vc RMS-V	PM DC	PM RF
a	6×10^{-4}	1.5×10^{13}	2460	6.5	3.3	2.1	1.1	----	0.57 W	129 mw
b	6×10^{-4}	1.5×10^{13}	2630	5.2	3.5	2.8	1.3	----	1.32 W	ZERO

IV. THEORETICAL EVALUATION

Tonks and Langmuir and recently Zollwig and Gottlieb have derived expressions for the frequency as a function of ion density, electron density and emitter temperature.⁽⁷⁾

$$f^2 = \frac{\frac{e^2 n_i}{\pi m_i}}{1 + \frac{e^2 n_e \lambda^2}{K T_e \pi}} \quad \begin{array}{l} T_e = \text{electron temperature} \\ \lambda = \text{wave length} \\ m_i = \text{ion mass} \end{array} \quad (1)$$

Eichenbaum and Hernquist⁽⁹⁾, Birdsall and Bridges,⁽⁷⁾ etc., show that instabilities in the plasma are the cause of rf oscillations. Within certain limits of n_i^+/n_e^- the potential between the electrodes oscillates between a positive and negative state. The values of n_i and n_e vary, of course, depending on the motive and its gradient in the emitter collector space. Close to the knee of the characteristics, the motive is very close to zero and n_e can be computed by the

ratio of I/V_e ; V_e = electron velocity

The ion concentration, n_i , cannot be calculated accurately. For an order of magnitude computation, the following assumptions will be made.

a. Only contact ionization is important. According to the Saha-Langmuir equation, a fraction q , of the atoms arriving at the emitter will be ionized. ⁽¹⁰⁾

$$q = \frac{1}{1 + 2 \exp - \left[\frac{\phi_e - I_i}{KT} \right]} ; I_i = \text{ionization potential of the K- atoms} \quad (3)$$

$$I_i = 4.32 \text{ volt}$$

$$\phi_e = 4.10 \text{ volt}$$

Since $\phi(e) = \phi(Ta)$ varies due to the patch effect expression 3 cannot give very accurate results.

b. The density, n , of the atoms between emitter and collector is given by an approximate expression of Nottingham

$$n = n_o \sqrt{\frac{2T_c}{T_e + T_c}} ; n_o = \text{density at } T_c \quad (4)$$

c. The atoms between emitter and collector move with a low velocity from the collector to the emitter corresponding to a collector temperature T_c . The atoms and ions leaving the emitter have a higher velocity corresponding to T_e , the emitter temperature. There are very few collisions in a low density plasma with the mfp d , the electrode distance.

Assuming a steady state condition and the continuity of the particle currents arriving and leaving the emitter, the ion density is given by

$$\frac{n_i}{n} = q \sqrt{\frac{T_c}{T_e + T_c}} ; \text{ from 3, 4, and 5 follows} \quad (5)$$

$$n_i = n_o \sqrt{\frac{2T_c}{T_e + T_c}} \left(\frac{1}{1 + \exp - \left(\frac{\phi_e - I_i}{KT} \right)} \right) \left(\frac{\sqrt{T_c}}{\sqrt{T_e} + \sqrt{T_c}} \right) ; \quad (6)$$

The frequencies could not be measured any more at the knee of the characteristics with motive zero, usually at -2.5 to -2.6 applied dc. The last position

with an observable frequency was -2 V dc. These frequencies were, therefore, compared with those calculated for zero motive.

Expression (6) was used to compute the ion densities, while (1) gave the computed frequencies. Table 5 shows the relations between various measured and calculated quantities. The frequencies could only be compared for a few cases, since rf noise made/impossible the observation at -2 volt.

Table 5
POTASSIUM CELL

T_c °K	T_e °K	n_K	n_{K^+}	$I = \text{ma/cm}^2$	n_e	$\frac{\text{rfpm}}{\text{dcpm}} \%$	Computed KC at -2.6V	Measured KC at -2 V
409"	2030"	4.8×10^{12}	1.08×10^{11}	1.27	5.68×10^9	4.0	674	630
406	2170	4.0×10^{12}	9×10^{10}	69.6	3.05×10^{10}	9.8	266	370
404	2300	3.9×10^{12}	9.35×10^{10}	222.0	9.35×10^{10}	25.2	---	---
408	2380	4.5×10^{12}	1.03×10^{11}	470.0	1.95×10^{11}	22.6	---	---
404	2520	3.5×10^{12}	8.07×10^{10}	1640.0	6.6×10^{11}	4.5	---	---
420	2040	9.0×10^{12}	2.18×10^{11}	12.4	5.05×10^9	0.75	980	670
422	2250	1.0×10^{13}	2.32×10^{11}	55.4	2.41×10^{10}	1.4	505	470
422	2375	1.0×10^{13}	2.39×10^{11}	448.0	1.86×10^{11}	23.0	---	---
450	2460	4.7×10^{13}	1.19×10^{12}	822.0	3.34×10^{11}	22.7	---	---
450	2630	4.7×10^{13}	1.2×10^{12}	3320.0	1.3×10^{12}	Zero	---	---

Generally, it appears that for ^{given} an ion concentration, no oscillations occur for a very low ratio of $\frac{n_e}{n_i}$. The oscillations start at ^a higher one, the rfpm/dcpm increases to a maximum and drops rapidly to a very low value.

EXPRESSIONS FREQUENTLY USED

ϕ_c	= collector or work function
ϕ_e	= emitter or work function
I_i	= ionization potential
J	= emitter current
$I=J/\text{cm}^2$	= current density
T_c	= collector temperature, $^{\circ}\text{K}$
T_e	= emitter temperature, $^{\circ}\text{K}$, approximately electron temperature
R_L	= load resistance
dc	= direct current
rf	= radio frequency
dcpm	= power maximum for dc
rfpm	= power maximum for rf
mw	= milliwatt
VTV	= vacuum tube voltmeter
RMSV	= root means square volt
$p(K)$	= potassium vapor pressure in mm Hg
$n=\text{At}/\text{cc}$	= atomic density, n_K = potassium density
n_i	= ion density
n_e	= electron density

Other expressions will be given at the proper place.

FIGURE CAPTIONS

- Fig. 1 Measurement of RF and DC Power Conversion
- Fig. 2 Voltage - Current Characteristics
- Fig. 3 Voltage - Current Characteristics
- Fig. 4 Voltage - Current Characteristics
- Fig. 5 Voltage - Current Characteristics
- Fig. 6 RF Frequency as a Function of Applied DC

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FIG. 2. VOLTAGE-CURRENT CHARACTERISTICS.

FIG.4: VOLTAGE-CURRENT CHARACTERISTICS:

FIGS: VOLTAGE-CURRENT CHARACTERISTICS:

FIG 1. MEASUREMENT OF D.C. AND RF. POWER OUTPUT,

6c -1 VOLT

6d -2 VOLT

FIG 6 RF Frequencies
As Functions of Applied DC

6b +1 VOLT

6a +3 VOLT