Notas de Fisica, Nº 5, 1952

METHODS OF OBTAINING HIGH VACUUM BY IONIZATION. CONSTRUCTION OF AN "ELECTRONIC PUMP".

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September, 1952

Calculations on the possibility of obtaining high vacuum in an electrical discharge are given. It is shown that in a simple d.c. gas discharge practically no real pumping action is possible; in such a discharge only clean-up, i.e. electrical adsorption, may be observed. A real pumping action only results if it is possible to get within a tube, such a high ion current by special arrangements that the number of ionized gas molecules transported with this current in one direction is greater than the number of gas molecules that will diffuse back in the opposite direction. - An electronic high vacuum pump of real pumping action has been built; it starts pumping at about 10^{-3} mmHg and gives an ultimate pressure lower than $5 \cdot 10^{-6}$ mmHg.

1. INTRODUCTION

The idea of obtaining high vacuum by ionization is quite old. Already in the "Poggendorf-Annalen" of 1858, J. Plücker[1] points out this possibility. Of course his conclusion cannot be accepted as whole; but he seems to be the first to observe electrical clean-up, i.e. adsorption of gases or vapors in an electrical gas discharge. The mechanism of clean-up is briefly explained in the following way[2]: Gas molecules are ionized and after this drawn to collectors of a negative potential where they will be adsorbed or "shot" in. A simple device of clean-up would operate as a "vacuum pump" only for a short time, because the adsorbing parts will soon become saturated. To obtain a continuous pumping action, the ions must be drawn to a fore vacuum side which is connected to a rough vacuum pump (rotary pump or mercury diffusion pump, o.a.). After being neutralized they will be pumped away. But the number of these ions has to be greater than the number of gas molecules which will diffuse back. This is necessary, but not sufficient to get a real pumping action.

2. ABOUT THE POSSIBILITY OF PUMPING ACTION

We will see now that it is not possible to construct a high vacuum pump with reasonable dimensions in a normal d.c. gas discharge. We assume the following model (see Fig. 1). We have a tube of x cm in length and a diameter of 2r cm. The cathode may be at A,

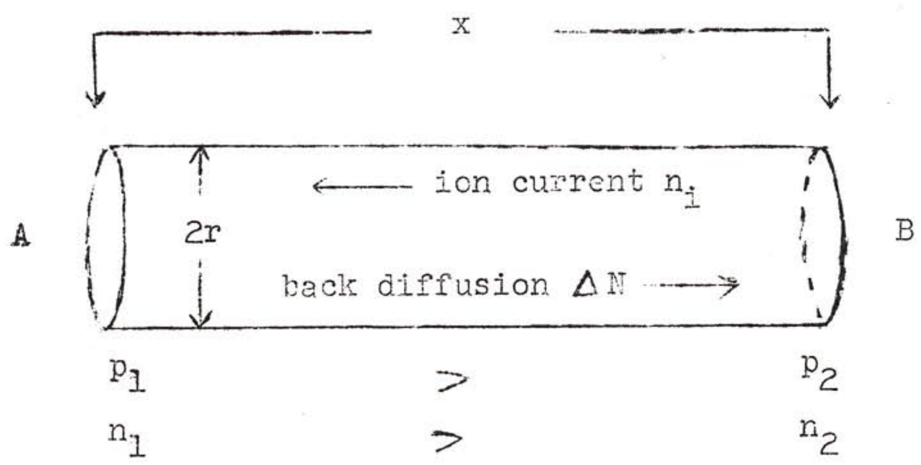

Fig. 1

and the anode at B. We claim a difference of pressure between the ends of the tube of $p_1 - p_2 > 0$. The density n_1 corresponds to pressure p_1, and the density n_2 (number of molecules per cm^3), corresponds to pressure p_2. The necessary assumption for setting up a pressure difference between the ends of the tube is:

(1) $$n_i > \Delta N,$$

i.e., number of ions/second greater than gas flow ΔN

This assumption is not sufficient from many points of view, as we shall see later.

To get an idea of the order of magnitude of the diameter

2r and of the length x of the tube in relation to the electrical values, we calculate both sides of the inequality (1).

The number of ions depends on the number n_e of electrons coming from the cathode and on the potential difference U between cathode and anode, and furthermore on the so called differential ionization $s_o(U)$, the pressure p, and the length of the electron path which may be as much as the length of the tube. As pressure and s_o will not be constant at every point of the tube, we must integrate over the length of the tube.

(2) $$n_i = n_e \int_0^x s_o(U_\xi)\, p(\xi)\, d\xi$$

But the differential ionization s_o is defined as the number of ions reduced to 1 mmHg and obtained for each electron that collides with gas molecules at least once on its path x. To get more accurate values we have therefore to replace in (2), n_e by a value:

$$n_e\left(1 - e^{-\frac{x}{\bar{\lambda}_e}}\right)$$

which gives the number of electrons that collide at least once on their path. $\bar{\lambda}_e$ is the mean free path of the electrons in the gas. For the number of ions we get now:

(3) $$n_i = n_e\left(1 - e^{-\frac{x}{\bar{\lambda}_e}}\right)\int_0^x p(\xi)\, s_o(U_\xi)\, d\xi$$

An electronic pump with hot cathode is only of interest if it acts at pressures lower than 10^{-4} mmHg, so that the correction of the number of colliding electrons is necessary. - To compute the other side of inequality (1), i.e. the number of the back diffusing molecules, we may apply the Knudsen law for a case where the mean free path is longer than the diameter of the tube:

(4) $$\Delta N = \frac{2}{3} r^3 \pi \bar{c}\, (n_1 - n_2)\, \frac{1}{x} ,$$

where $\bar{c}$ is the average thermal velocity of the gas molecules. Furthermore, we are not too pretentious if we claim that our pump reduces the pressure at least down to 1 %, i.e, to 10^{-6} mmHg. Then we can neglect n_2 against n_1. Our inequality (1) now gets the following form:

(5) $$n_e\left(1 - e^{-\frac{x}{\bar{\lambda}_e}}\right)\int_0^x p(\xi)\, s(U_\xi)\, d\xi > \frac{2}{3} r^3 \pi \bar{c}\, n_1 \frac{1}{x}$$

We may take out of the integral p (ξ) and eliminate it by an average pressure $\bar{p}$. As we may derive from measured[3] values of s_o, we can write approximately for the integral

$$\int_0^x s_o(U_\xi)\,d\xi = x$$

which would be favorable to a shorter tube x.
Substituting n_e by the current I_e, we get the following inequality for the length x of the tube:

$$x^2\left(1 - e^{-\frac{x}{\bar{\lambda}_e}}\right) > A\frac{r^3}{I_e} \tag{6}$$

where

$$A = \frac{2\pi\bar{c}n_1\bar{e}}{3\bar{p}}$$

and $\bar{e}$ the elementary charge.

$$f(x;\,I_e;\,r) = x^2\left(1 - e^{-\frac{x}{\bar{\lambda}_e}}\right) - A\frac{r^3}{I_e} \tag{7}$$

Our electronic pump would operate for all values of x, I_e, and r that give positive values for the function (7). Introducing the numerical values for air at an average pressure in the tube of $\bar{p} = 10^{-4}$ mmHg, we get

$$\bar{\lambda}_e = 4\sqrt{2}\,\bar{\lambda}_{air} = 260\text{ cm}$$

$$A = 508 \text{ amps/cm}$$

Computing the zeros of the function (7) for electron currents between .001 and 10 amps and for reasonable values of the tube radius r = 0.5 and 1.0 cm, we obtain the minimum length x_{min} of the tube. To get a pumping we have to increase the current I_e that corresponds to x_{min}. In Table I we find the computed values. In the first column we find the electron current I_e, in the second the minimum length x_{min} of the tube, in the third, the ion current I_i for the double value of I_e, and in the fourth column finally, the pumping speed at 10^{-4} mmHg, when we make 2 I_e amps pass through the tube. The ion current has been computed by using formula (3) for the number of ions; with the values of our case we obtain the formula

$$I_i = 10\frac{r^3}{x} \text{ (amps).} \tag{8}$$

Table I

Minimum length x_{min} of discharge tube suitable for pumping

A) r = 1.0 cm

I_e (amps)	x_{min} (cm)	I_i (amps) ion current	S (liters/sec) at 10^{-4} mm Hg
0.001	735	$1.4 \cdot 10^{-4}$	0.13
0.01	278	$3.6 \cdot 10^{-4}$	0.35
0.1	118	$8.5 \cdot 10^{-4}$	0.8
1.0	53	$1.9 \cdot 10^{-3}$	1.8
10.0	24	$4.2 \cdot 10^{-3}$	4.0

B) r = 0.5cm

0.001	304	$4.1 \cdot 10^{-5}$	2.5
0.01	128	$9.8 \cdot 10^{-5}$	6.0
0.1	56.8	$2.2 \cdot 10^{-4}$	13.6
1.0	25.8	$4.8 \cdot 10^{-4}$	30
10.0	12.0	$1.0 \cdot 10^{-3}$	64

The pumping speed at 10^{-4} mmHg can be calculated with the formula derived from (4)

(9) $$S = 96.4 / r^3 x \quad \text{(liters/sec)}.$$

if we use twice the value of the electron current I_e calculated for the minimum length.

Reasonable values for the minimum length are only obtainable for large electron currents. There are no technical difficulties in getting sufficient electrons emitted from hot cathodes, but their space charge will be enormous, and very high voltage must be applied to get the electrons through the long tube. Electrons will attach to the glass walls and charge it negatively and by this, sensibly change the electric field. Further calculations on the necessary voltage point out that this must be of the order of 10^5 volts, even for lower currents, as with these we calculate much longer minimum lengths.

From this we can conclude that the construction of an electronic high vacuum pump in a simple gas discharge tube is not possible.

We must emphasize that we assumed favorable conditions in calculating pumping action of a simple gas discharge. We did not consider re-combination of ions, the high electron bombarding energy, and other problems. Furthermore, we must say that s_o is much smaller at higher voltages and that some electrons will hit the walls and not arrive at the anode at all.

We have to find a way to increase the path of the electrons without increasing the length x of the tube. There are two different ways:

1. that of making the electrons oscillate in the axis of the discharge tube on screw paths [4, 5]

or

2. that of forcing the electrons in spiral paths by a magnetic field within a cylindrical electrodes system, as for expl. in a magnetron valve or cyclotron.

Instead of our inequality (5) we have now:

$$n_e\left(1-e^{-\frac{\nu x}{\bar{\lambda}_e}}\right)\nu\int_0^x p(\xi)\, s_o(U_\xi)\, d\xi > \frac{2}{3} r^3 \pi \bar{c}\, n_1 \frac{1}{\lambda} \qquad (10)$$

where ν denotes the increase factor of the electron path.

Substituting the numerical values in (10) as we did before, and neglecting the exponential part for sufficiently high values of ν, we obtain the following numerical inequality for the tube length x:

$$x > 22.6\sqrt{\frac{I}{\nu I_e}} \qquad (11)$$

A simple example shows that the conditions for the construction are feasible.

$r = 1$ cm ; $\nu = 20$; $I_e = 0.1$ amps ; $x_{min} = 16$ cm
$S = 6$ liters/sec at $I_e = 0.2$ amps and $p = 10^{-4}$ mmHg

Since the ion current in this example would be of the order of 5 mA, there will be practically no negative space charge, consequently the voltage can be much smaller.

It is easy to mistake a clean-up for a pumping action, i.e. adsorption of the ions on the walls or on the electrodes. All experimental work done in this field must be considered very critically. As far as we know, R. Champeix[6] is the first to have constructed an experimental pump; but it seems to us that he observed clean-up in his gas discharge tube without special arrangement for prolonging the ionizing electron path, and not a real pumping action in our sense.

3. CONSTRUCTION OF AN "ELECTRONIC PUMP" AND ITS PUMPING CHARACTERISTICS

In our laboratory we constructed an electronic pump[7] using experience obtained from our earlier work in this field in 1940.[5] The tube consisted of an incandescent cathode, an anode of ring shape and a third annular electrode which was on the same potential as the cathode. An electron current of about 10 mA was emitted by the cathode and kept oscillating through the annular anode at about 2000 volts or more; a small magnetic field parallel to the axis of the tube kept the electrons on spiral paths in the center of the tube, away from the anode. In such a tube a very intensive clean-up was formerly observed and the adsorbed gas was found at the glass walls which had become negatively charged by secondary electron emission. In our new electronic pump model[7], Fig. 2, we opened the glass wall at four spots between the two rings, but nearer to the anode. We connected four tubes and at the entrance of each we put a ring electrode at slightly negative potential. These tubes were all joined together and connected at F to a common rotary oil pump as a fore pump. In another experimental device, we made a hole at F_1 between the two lead-in wires of the cathode and connected a fifth tube there which leads as well through F to the fore pump. The volume to be brought to high vacuum was connected to the opposite side of the hot cathode at H. At the entrance of the connection tube H, another annular electrode B was sealed in a coaxial position. It was maintained at positive potential to prevent ions from running back to the high vacuum. The pressure at the high vacuum side H was measured by a Pirani gauge and an ionization gauge type VG - 1 A .

4. OPERATIONAL PROPERTIES OF THE ELECTRONIC PUMP.

A volume of about 500 cm^3 connected at H (Fig. 2) was pumped from a pressure of about 10^{-3} to $1.0 \cdot 10^{-5}$ mmHg, or sometimes $5 \cdot 10^{-6}$ mmHg, in less than one second. Although the pumping was repeated more than 30 times without any change in the arrangement, we did not observe any saturation. But as simple calculations prove that even three times would give a mono-molecular layer on the inner wall of the pumping tube, this pressure decrease could not have been caused by clean-up, i.e., adsorption at the walls. The adsorbed layer cannot be thicker than 1.7 times that required to form a monolayer, as we already found in our previous work[5]. Therefore, the observed decrease of pressure must have been a real pumping action. This was proved as well by the following experiment. We let in small quantities of gas at H and measured the increase of pressure at the fore vacuum side, but still a pressure difference was maintained.

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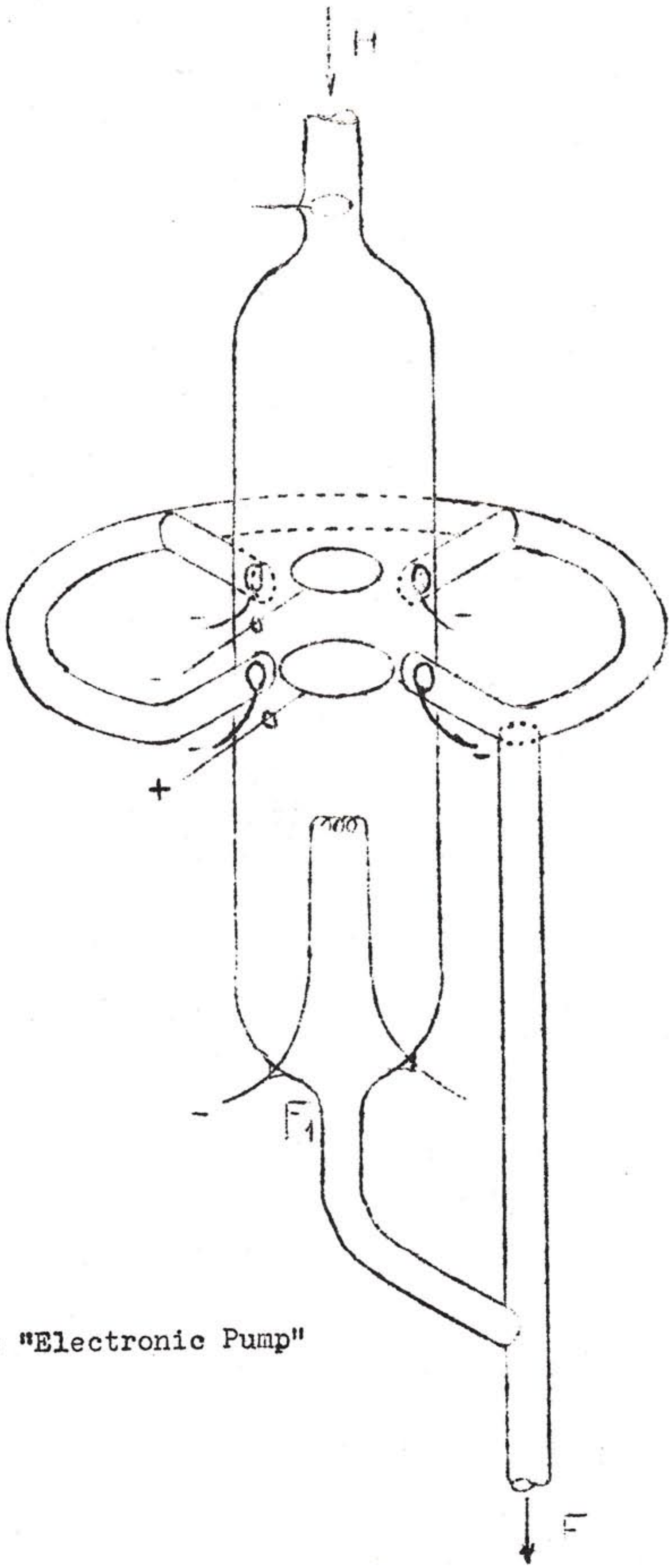

Fig. 2

Model of the "Electronic Pump"