INVESTIGATION OF A DIRECTED BEAM OF HIGH-SPEED ELECTRONS THROUGH MERCURY VAPORS IN A HEATED-CATHODE DISCHARGE TUBE

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From *Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki,*
Vol. 8, No. 4, 1938

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1966

NASA TT F-370

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Translation of "Issledovaniye napravlennogo potoka bystrykh elektronov v razryade s nakalennym katodom v parakh rtuti." Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki, Vol. 8, No. 4, pp. 436-443, 1938.

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INVESTIGATION OF A DIRECTED BEAM OF HIGH-SPEED ELECTRONS THROUGH MERCURY VAPORS IN A HEATED-CATHODE DISCHARGE TUBE

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ABSTRACT

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The electron velocity distribution function in a directed beam is strictly true only near the cathode. Around the cylindrical probe in a discharge ⊥ to the axis a variable nonsymmetric ionic layer forms. Electron reflection is better from a poorly degassed probe than from a completely degassed one.

Author

A method is described for investigating directional flows which do not depend on the law for the extrapolation of ion current. Directional flows were investigated as a function of the discharge current and the distance from the cathode. /436*

It has been established that the identification of the distribution function for the electron velocities in a directional flow with the Maxwellian distribution containing a superposed transfer motion along the tube axis is a rough approximation.

1. Introduction

The validity of the linear extrapolation of ion currents usually used to separate electron and ion currents flowing in the probe circuit has been questioned in recent works (refs. 1 and 2).

Since the same criticism pertains to reference 3, which was published by one of the authors at an earlier date, we conducted new experiments which are free of the above shortcomings.

It follows from our experiments without any doubt and in complete agreement with the views of Langmuir (ref. 4) that there is a directional beam of

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*Numbers given in the margin indicate the pagination in the original foreign text.

high-speed electrons in a discharge which has a certain transport velocity u. For an observer moving along the axis of the discharge tube with a velocity u, the electrons of the beam have a velocity distribution which in the first approximation coincides with the Maxwellian distribution.

2. Equipment and Method of the Experiment

All experiments were conducted with discharges in mercury vapors. Figure 1 shows the arrangement of the electrodes in the discharge tube. The tube contains an oxide cathode O, anode A, tungsten filament C, placed perpendicular to the axis of the tube, and a movable flat probe D whose rear side (which faces the anode) is covered with mica. The diameter of the flat probe D was equal to 9 mm, the length of the tungsten filament was 35 mm and its diameter was 0.1 mm. The discharge tube was connected by a long narrow glass tube to the operating vacuum installation and was submerged in a vessel with flowing water. It should be pointed out that the results of the experiments could not be repeated if the tube was in air and if its wall temperature was not constant. The probe D could be displaced along the axis of the tube and remained at its center at all times. /437

The experiments were conducted in the following manner. After the usual processing of the electrodes when the vacuum system was turned on, a discharge occurred between the oxide cathode O and the anode A whose current I_A varied within the range of several amperes while the voltage drop at the tube V_A varied from 18-19 V.

Next the tungsten filament C was fed with a sufficiently high negative potential V_C (in the future the anode potential is considered as 0), and the filament was heated by the current from a battery. As a result of this, a layer of positive ions formed around the filament C and a flow of fast primary electrons was directed from the filament into the discharge (refs. 3 and 5).

Thus by having two cathodes in the tube we used cathode O to produce the discharge and cathode C to produce a flow of high-speed electrons.

In all the previous works known to us (refs. 1, 3 and 6), when directional flows were studied, the discharge produced by the cathode which generated the flows by itself was used. The tube we designed makes it possible to separate these two functions of the cathode and study the properties of electron beam passing through the discharge with predetermined parameters and desired velocity. /438

Since the emission current from C is less than from O, the current of electrons from the tungsten filament has a weak effect on the basic discharge produced by the oxide cathode. Probe V is used to analyze the properties of the directional flow of fast electrons.

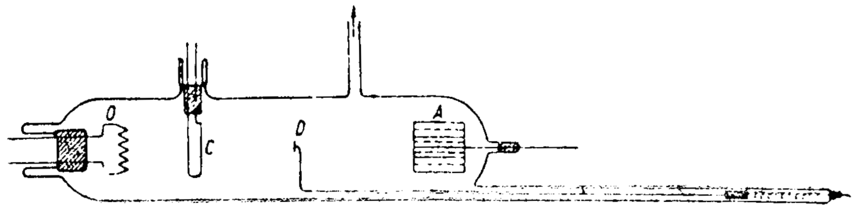

Figure 1. Discharge tube.

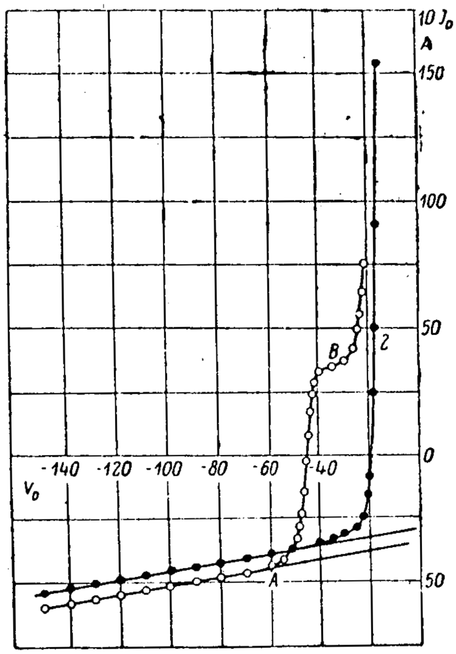

Figure 2. Typical volt-ampere characteristics of probe D, with cold (curve 2) and incandescent (curve 1) tungsten filament C: $I_A = 1$ A,

d = 15 mm, $V_C = 45$ V, $I_C = 50$ mA.

Typical volt-ampere characteristics of probe D with a cold (curve 2) and incandescent filament C (curve 1) are shown in figure 2, where the current in the anode circuit traveling from the oxide cathode O was equal to $I_A = 1$ mA and probe D was at the distance of d = 15 mm from the filament C. The potential difference between the filament C and the anode A was equal to $V_C = 45$ V. The discharge current produced by the filament C was equal to $I_C = 50$ mA.

The sharp rise in curve 1 at point A is explained by the fact that probe D with a potential of 60 V corresponding to point A began to receive the flow of fast primary electrons traveling from the filament C. By extrapolating the ion current and making up the difference between the resulting current I_D and the ion current, we find the magnitude of the directional current from the filament C falling on probe D (for details see references 3 and 4). Figure 3 shows the variation in the magnitude of the directional current I_D^n, obtained in this manner, falling on the probe D from the retarding potential of the probe. The same figure shows the curve obtained from the characteristics of the directional current by means of its numeric differentiation. It is known (ref. 7) that such a curve gives the variation in the distribution function of the electron velocity components which are normal to the surface of the probe. The sharp peak obtained on the distribution curve shows that a sufficiently monochromatic beam of electrons falls on probe D. It is obvious that the potential corresponding to the maximum on the distribution curve is equal to the velocity associated with the transport of the directional electron flow. This determination of the directional velocity of electron flow has shown that the directional velocity is always equal to the potential V_C of cathode C.

Because cathodes O and C are independent, by a proper selection of voltages we can always place point A (fig. 2) at such a place of the characteristic

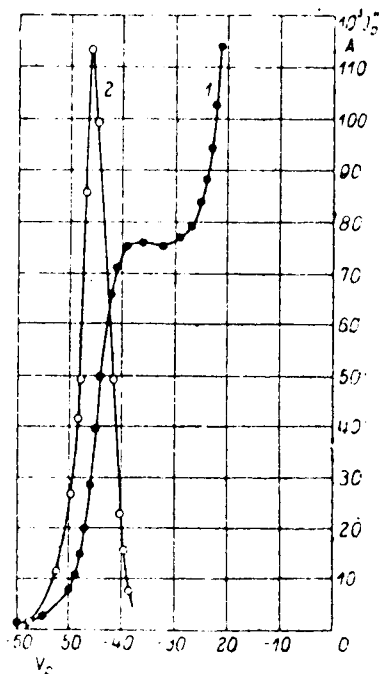

Figure 3. Typical characteristics of the directional current of high-speed electrons falling on probe D. Curve 2 gives the distribution for the velocity components of electrons in a flow normal with respect to probe surface.

so that the entire part AB due to the directional current will lie in the region of voltages where the ion current varies according to a linear law. By proceeding in this manner we could extrapolate the ion currents along a straight line with confidence.

3. Variation in the Flow of Fast Primary Electrons As a Function of the Discharge Current

To study the properties of the primary beam of electrons we measured the volt-ampere characteristics of the directional electron current.

Figure 4 shows a series of such characteristics for the directional current measured with different values of the discharge current I_A but with a constant current from probe C (I_C = 50 mA) when the distance between probe D and filament C was 15 mm and when the negative voltage on filament C was 45 V. The upper curve corresponds to the case when the discharge current from the oxide cathode 0 is equal to 0 (i.e., the oxide cathode is disconnected) and the tungsten cathode itself serves as the basic cathode sustaining the discharge.

All the characteristics exhibit saturation whose magnitude in the future will be designed by i_0. We can see from figure 4 that as the discharge current I_A flowing from the oxide cathode 0 is increased, the magnitude of directional current saturation falling on probe D is also increased. To analyze the characteristics of the directional current we followed Langmuir (ref. 4) and assume in the first approximation that the electrons of the primary beam have a transport velocity u_0 with a superposed Maxwellian velocity distribution having a temperature T. /439

In this case the magnitude of the directional current I_D^n falling on probe D is given by the equation (ref. 3)

$$I_D^n / i_0 = \tfrac{1}{2}\left[1 + \Phi(x)\right], \qquad (1)$$

where

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy \quad \text{and} \quad x = \sqrt{V_C/V_T} - \sqrt{V_D^0/V_T} \qquad (2)$$

In equation (2) V_D^0 is the absolute value of the retarding potential of probe D relative to the ionized gas, V_C is the transport velocity of the

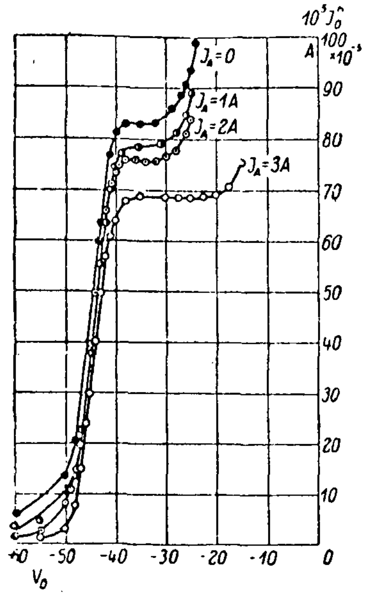

Figure 4. Characteristics of the directional current of fast electrons falling on probe D which is at a distance of 15 mm from filament C for different values of the discharge current I_A flowing from the oxide cathode A, and a constant discharge current from filament C equal to 50 mA. $V_C = -45$ V.

directional electron flow expressed in terms of the potential while V_T is given by the equality

$$eV_T = {}^3/_2 kT,$$

where e is the electron charge, k is the Boltzmann constant, and T is the electron distribution temperature in the flow.

If we designate by Φ^{-1} the function which is the inverse of the Gauss /440 function $\Phi(x)$, we have

$$\Phi^{-1}\left(2\frac{I_D^n}{i_0} - 1\right) = \sqrt{\frac{V_C}{V_T}} - \sqrt{\frac{V_D{}^0}{V_T}}. \tag{3}$$

From (3) we see that $\Phi^{-1}(2\ I_D^n/i_0 - 1)$ is a linear function of the square root of probe potential DV_D^0 and that we can determine the temperature of the superposed Maxwellian distribution from the slope of this straight line.

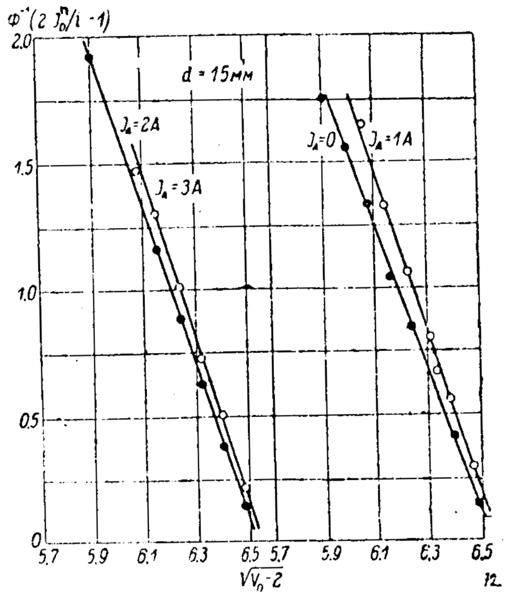

Figure 5. Determination of temperature of electron distribution in flow.

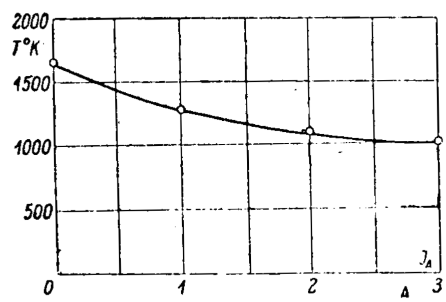

Figure 6. Variation in temperature T of electron distribution in a flow as a function of discharge current I_A.

By using the characteristics shown in figure 4 and plotting the relationship $\Phi^{-1}(2\ I_D^n/i_0 - 1)$ as a function of $\sqrt{V_D^0}$ we obtain a line shown in figure 5.

From figure 5 we can see that the points computed for each characteristic fall on a straight line with remarkable accuracy. The latter situation proves that at a distance of 15 mm from filament C the distribution function for electron velocities in the directional flow can still be presented as a Maxwellian distribution with a superposed motion along the tube axis. Figure 6 shows the variation in the temperature of the Maxwellian distribution of electron velocities in a directional flow as a function of the discharge current I_A. As we can see, the temperature of the electrons in the flow is close to the temperature of the filament C and as discharge current I_A increases, it decreases slightly.

4. Deformation of the Ion Layer Around Cathode C

From the family of characteristics for the directional current shown in figure 4, it is clear that as the discharge current I_A increases, the directional current of fast electrons I_D^n falling on the probe D increases.

At first we assume that the increase in the directional current falling on probe D is due to the focusing of electrons toward the center of the tube, which must increase with the discharge current through the tube.

To verify the last proposition we manufactured a tube in which the cathode C was surrounded by three probes of type D. Probe 1 was situated perpendicular to the axis of the tube facing the center of the filament just like probe D in figure 1; probe 2 was in the same plane as probe 1 but faced the end of filament C, while probe 3 was in the plane perpendicular to the first two facing the center of filament C, i.e., its plane was perpendicular to the axis of the tube. All the probes were of the same diameter and were at a distance of 15 mm from filament C. Characteristics of the same type as shown in figure 4 taken by means of these probes show that both probes 1 and 2 received a directional current which increased with the discharge current I_A. This contradicts the existence of focusing because if focusing of fast electrons did take place in the tube then the current falling on probe 2 would decrease. We note that the directional current i_0 falling on probe 3 decreased as the discharge /441 current was increased. Consequently we can maintain that the focusing of a beam of fast directional electrons along the axis of the tube does not take place. Therefore we have assumed that the increase in the current of the directional electron beam falling on probe D and occurring when there is an increase in the discharge current is due to the deformation of the ion layer around filament C. As a result of this there is a change in the distribution of the directional electron flow around filament C.

Indeed, in an earlier work published by one of the authors (ref. 8), it was shown that the form of the ion layer around a flat probe open on both sides and placed in a mercury vapor discharge depends on its orientation with respect to the axis of the tube. If the discharge currents are weak and the flat probe is perpendicular to the axis of the tube, it can be observed with the naked eye that the thickness of the ion layer on the side of the probe facing the cathode is several times less than the thickness of the layer on the side of the probe facing the anode. If the discharge current is increased with a constant potential on the probe, the thickness of the layers on both sides of the flat probe decreases while the difference between their values becomes less noticeable. If the plane of the probe is situated parallel to the axis of the tube, then there is a completely symmetric uniform ion layer around the probe.

Undoubtedly, around the cylindrical cathode C situated perpendicular to the axis of the tube there must also be a nonsymmetric ion layer. However, the visual observation of such a layer is impossible because the thickness of this layer is such that no darkening around the probe can be observed on the discharge background.

If we maintain constant the potential V_C of cathode C and the current I_C, and begin to increase the discharge current I_A, ionization will increase and as pointed out above, the dimensions of the ion layer around the cathode C will begin to decrease while its form will become more and more symmetric. As a result of this the directional current from the incandescent cathode C will propagate uniformly around the probe C and part of the directional flow falling on probe D will begin to increase with the discharge current.

It is curious that an increase in the directional current of fast electrons falling on probe D which takes place due to the deformation of the ion layer around cathode C is so large that it is not compensated by the scattering action of newly occurring ions and electrons whose density increases together with the discharge current.

Thus it follows from the above that the value of the saturation current of directional electrons falling on probe D depends on the form of the ion layer.

The above method can be used to investigate the symmetric properties of the ion layer which occurs around any probe if the probe is covered with a layer of oxide paste and is heated.

5. Properties of Fast Electron Flow Along the Tube Axis

To study the properties of fast electron flow along the axis of the tube we placed the probe D at various points in the discharge. Figure 7 shows the characteristics obtained in this manner for the directional flow of electrons taken for different distances of probe D from filament C when the discharge current from the oxide cathode was $I_A = 0.75$ mA and when there was a negative voltage on the filament C equal to $V_C = 45$ V. The discharge current from filament C in this case was equal to $I_C = 50$ mA.

It follows from the characteristics that as we move away from the filament C the saturation of the directional electron flow falling on probe D becomes less pronounced. The latter situation is due to the scattering of the fast electron flow by the discharge. Figure 8 shows the results obtained from processing the characteristics presented in figure 7 using the method described in section 2. As we can see from figure 8, at a distance of 20 mm from filament C the expression $\Phi^{-1} \left(2 \frac{I_D^n}{i_0} - 1\right)$ is no longer a linear function of $\sqrt{V_D^o}$. Consequently, under conditions existing in our experiments, at a distance of 20 mm /442

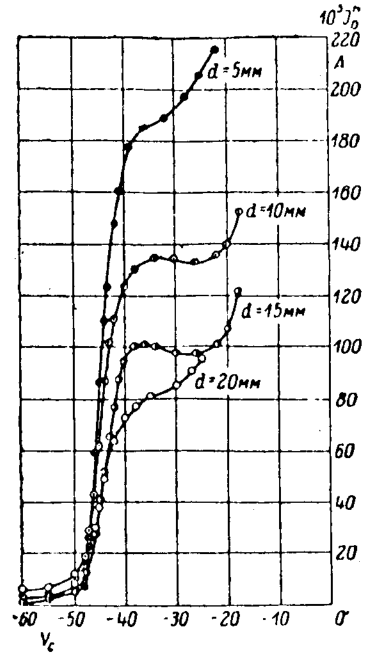

Figure 7. Characteristics of directional flow taken for different points on the tube. I_A = 0.75 mA.

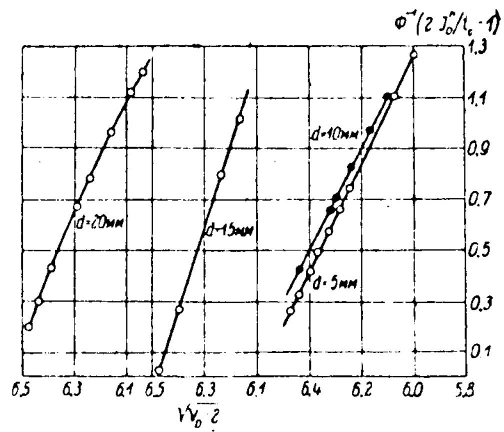

Figure 8. Variation in the distribution temperature of electrons with distance d from filament C.

from filament C the distribution function for the electron velocities in the directional beam no longer follows the law which was assumed in the derivation of equation (3). In other words, the identification of the distribution function for the electron velocities in the direction of law with the Maxwellian distribution having a superposed transfer motion along the axis of the tube, becomes only a rough approximation which under our conditions is valid only at distances from the filament which are less than 20 mm.

Generally speaking, the distribution of electron velocities in a directional flow does not follow such a simple law.

The temperature T of the random electron motion in a directional flow is close to the temperature of the incandescent filament C and decreases slightly with distance.

6. Reflection of Electrons from the Surface of the Probe

In a previous work, one of the authors (ref. 3) determined the coefficient for the reflection of electrons from the surface of the probe by comparing the characteristics of probes oriented in a different manner and placed at different points in the discharge tube.

Further experiments show that the discharge occurring in the tube with an incandescent tungsten cathode, when the discharge current is small, is not /443 homogeneous along the discharge axis. Thus, for example, the density of slow electrons decreases in the direction from the cathode to the anode. Therefore, in comparing the characteristics of probes placed at different points along the tube axis we took into account two effects: the effect of electron reflection from the probe and the nonhomogeneity of the discharge itself.

In order to illustrate the reflection of electrons from the surface of the probe, we took several characteristics of the directional current when the probe D had not yet been sufficiently degassed. It is known that in this case the reflection of electrons is particularly pronounced. The characteristics obtained in this manner are shown in figure 9 where characteristic No. 2 was

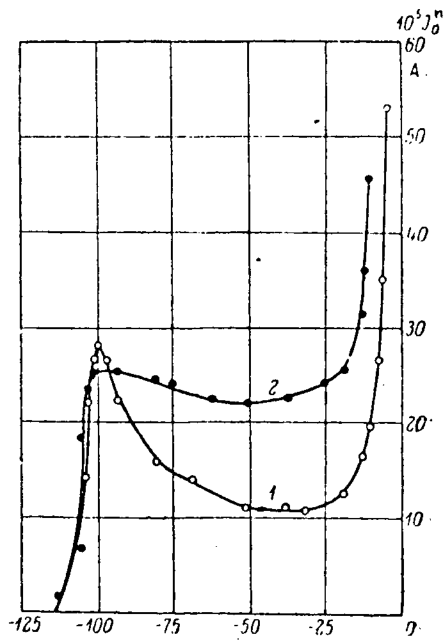

Figure 9. Reflection of electrons from the surface of a poorly degassed probe.

taken after a prolonged degassing of probe *D* while characteristic No. 1 was taken at the beginning of the tube aging. As we can see from figure 9, the characteristics do not exhibit a sharply defined saturation; on the contrary, after a certain maximum is reached, the magnitude of the directional current begins to decrease sharply (Dyntron effect), which is due to the reflection of electrons from the surface of the probe. After prolonged degassing the reflection of electrons from the probe becomes less.

7. Conclusions

The following conclusions have been established from the above investigations:

1. The identification of the distribution function for electron velocities in a directional flow of fast electrons with the Maxwellian distribution having a superposed transport motion along the axis of the tube, is only a rough approximation which is valid only at short distances from the cathode which forms the flow.

2. A nonsymmetric ion layer forms around a cylindrical zone which is placed in the discharge perpendicular to the axis of the tube. The symmetric properties of this layer vary with the increase in the ion current falling on the probe.

3. The reflection of the electrons from a poorly degassed probe is greater than from a degassed probe.

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Translated for the National Aeronautics and Space Administration
by John F. Holman and Co. Inc.

NASA-Langley, 1966 F-370