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It has been pointed out in a recent paper by Lüthi and Seelig (1977) that current limitation is of importance for ion laser discharges in noble gases and mercury, and a better understanding of this phenomenon would be useful to optimize laser outputs. These authors have also summarized results from a large number of experiments and compared them with available theories. In this letter limitation of the steady discharge current by saturation of the ion flux at a double layer will be discussed and compared with the experimental results.

An upper limit for the electron current density at a stationary double layer in a low pressure arc was given by Andersson et al. (1969). Although double layers in general may show large voltage fluctuations with frequencies in the ion sound regime, it is well-known that about stationary double layers with only small voltage fluctuations can form at the cathode end of the positive column (Crawford and Freestone 1963, Andersson 1977). For commonly used geometries the cathode side of the layer is then in contact with a gas reservoir with a controlled pressure so that the atom number density N_o and the temperature T_o are known there. The gas flux directed towards the layer becomes $N_o\bar{V}/4$ where $\bar{V} = (8kT_o/\pi m_i)^{1/2}$ and m_i is the ion mass. To maintain the layer, an ion current density j_i must flow towards the layer from the positive column. In a low pressure arc this current originates from ions formed locally close to the layer by electron impacts with neutral atoms. Accordingly we must have

$$j_i < eN_o(kT_o/2\pi m_i)^{1/2} \qquad (1)$$

for, if j_i were larger than this value, a region on the anode side of the layer would be continuously depleted of mass and a rarefaction region would arise where it would be impossible to maintain a stationary plasma. Thus a violation of (1) is expected to represent the final breakdown of the arc discharge. In equation (1) e is the positive elementary charge assuming singly charged ions. When j_i approaches the upper limit given by (1), the plasma on the anode side of the layer approaches an ionisation degree of 100% due to the strong local gas rarefaction there which was observed experimentally by Sandahl (1971). In practice current limits are determined as the currents when large amplitude voltage fluctuations appear over the layer. Sandahl's experiment suggests that this may occur for values of j_i about 20% smaller than the upper limit predicted by (1). Here we shall neglect the possibility of such a difference which, however, should be remembered in a rigorous comparison between experiment and theory.

Introducing the notation

$$\kappa = \frac{j_e}{j_i}\sqrt{\frac{m_e}{m_i}} ,$$

where j_e is the electron current density at the layer and m_e the electron mass, we get from (1)

$$j_e < \kappa e N_o (kT_o/2\pi m_e)^{1/2} \qquad (2)$$

In the Langmuir model for a double layer (Langmuir 1929) the momentum of trapped particles on each side of the layer is neglected, and κ equals unity. Under low pressure discharge conditions we can neglect the momentum of trapped ions because the ion-neutral collision mean free path is usually larger then the tube radius R and backscattering of accelerated ions towards the layer is negligible. However, since electrons in the positive column are specularly reflected at the tube wall, electrons can be backscattered towards the layer even when the electron mean free path is much larger than R. Accordingly trapped electrons on the anode side of the layer can significantly contribute to the momentum balance of the layer even at very low pressures. A simple model taking this into account is obtained by introducing the pressure of trapped electrons into the Langmuir model, in which it is assumed that ions and electrons transmitted through the layer are monoenergetic beams with negligible initial velocities. This gives

$$\kappa = \frac{1}{1+\frac{n_{tr}}{n_e}\frac{kT_e}{2eV_o}} \tag{3}$$

Here n_{tr} is the density of the trapped electrons and T_e their temperature, n_e is the density of primary electrons transmitted through the layer and V_o is the layer voltage. The values of the densities refer to the anode side layer edge, and it is assumed that no trapped electrons can reach the layer edge at the cathode side. From (3) it is clear that κ will assume a value less than unity under low pressure discharge conditions. A model also taking the initial ion velocity into account was given by Crawford and Cannara (1965). They found that n_{tr} typically could be up to four or five times larger than n_e, and from their results κ can be obtained as a function of kT_e/eV_o (Table 1). For comparison κ-values found by Andrews and Allen (1971) are also given. These authors also introduced trapped ions with a finite but very small temperature. The results obviously agree closely unless kT_e/eV_o approaches unity.

Table 1. Theoretically calculated values of $\kappa = (j_e/j_i)(m_e/m_i)^{1/2}$ at a double layer by Crawford and Cannara (1965) and Andrews and Allen (1971). V_o is the layer voltage and T_e the temperature of trapped electrons.

kT_e/eV_o	0.1	0.2	0.3	0.4	0.5
κ(C.C. 1965)	0.71	0.57	0.44	0.35	0.28
κ(A.A. 1971)	0.71	0.55	0.43	0.32	0.21

To compare the results with experiments we must also take into account that the layer usually forms a surface, which is convex towards the gas reservoir and has an area larger than the tube cross-section. Denoting the maximum current density in the positive column by j_z we can rewrite (2) as

$$j_z = f\kappa e N_o (kT_o/2\pi m_e)^{1/2}. \qquad (4)$$

Here f is the ratio between the area of the layer surface and the tube cross-section. In many cases the layer surface can be approximated by a hemisphere (Andersson 1977) yielding $f = 2$ as a typical value.

Now Lüthi's and Seelig's synthesis of experimental data for mercury arcs up to $pR \approx 5$ mTorr cm is consistent with a limiting current density of the form

$$j_z \approx 0.5\ eN_o (kT_o/2\pi m_e)^{1/2} \qquad (5)$$

which would agree with (4) if $\kappa f \approx 0.5$. Assuming $f = 2$ this would require $\kappa \approx 0.25$ which is consistent with the data in Table 1 if kT_e/eV_o assumes a fixed value closely equal to 0.5 at the current limit. The found value of κ is also consistent with the measurements of electron energy distributions by Andersson (1977). He found a Maxwellian distribution of trapped electrons on the anode side of the layer with a typical temperature given by $kT_e/eV_o \approx 0.3$ which would give $\kappa \approx 0.4$ according to Table 1. However, there was also a fast electron population, peaked at an energy corresponding to the layer voltage, with an electron number density which could be up to three times larger than the density n_e of the primary electrons, when this is estimated from the measured energy distribution at the cathode side of the layer and the known layer voltage. The building up of this fast electron population may partly be due to the curved layer surface, but obviously elastic backscattering of fast electrons would also be an efficient mechanism. Elastically backscattered fast electrons would reduce κ further because they give rise to an additional term in the denominator of equation (3) of the form $n_s \langle v^2 \rangle_s/(n_e 2eV_o/m_e)$. Here n_s is the density of elastically scattered electrons and the brackets mean average over their velocity distribution. For an isotropic distribution with an average speed sharply peaked at $(2eV_o/m_e)^{1/2}$ we get $n_s < v^2 >_s/(n_e 2eV_o/m_e) = $ $= n_s/3n_e \approx 1$ when it is assumed that $n_s \approx 3n_e$ as estimated from Andersson's experiments. This additional term would reduce κ to a value between 0.2 and 0.3.

We find that the experimentally determined factor 0.5 in equation (5) can be explained by a reduction of κ due to the momentum of trapped electrons which strongly supports a current limitation model based on a double layer.

So far only low pressures have been considered so that the mean free path for the positive ions is larger than the tube radius. When the gas pressure is increased, it is likely that the first type of collision becoming of importance at the cathode side of the layer is charge transfer collisions between ions accelerated in the layer and neutral atoms. We shall consider the case when $N_oR >> 1/Q_{tr}$. Here Q_{tr} is the charge transfer cross-section for an ion moving in its parent gas. One can estimate $Q_{tr} \approx 10^{-14}$ cm^2 for mercury and about $5 \cdot 10^{-15} cm^2$ for argon (Massey and Gilbody, 1974). This gives $N_oR >> 2 \cdot 10^{14}$ cm^{-2} or $p_oR >> 5$ mTorr cm for the analysis below to be valid. Here p_o is the pressure corresponding to N_o at 300 K. We shall also consider the conditions at the current limit only when j_i/e is assumed to be equal to flux of atoms from the gas reservoir to the layer. Then the plasma on the anode side of the layer is fully ionized and no neutral atoms move from the layer into the gas reservoir. Since $N_oR >> 1/Q_{tr}$, all ions will have collided with atoms within a distance $L << R$, and the ion stream has then been transferred into a stream of fast atoms moving from the layer into the gas reservoir. The reverse collisions between fast atoms and slow ions can be neglected because the ionization degree at the cathode side of the layer is not more than a few percent. The fast neutral stream carries j_i/e atoms per unit area and unit time, and it is made up of atoms which before the charge transfer collisions were moving towards the layer with an average velocity $\overline{V}/2$. Assuming now that the flux of atoms towards the layer is $N_o\overline{V}/4$ at a distance L from the layer, obviously only $N_o\overline{V}/4-j_i/e$ atoms will reach the layer. At the current limit this must be equal to j_i/e so we get $j_i = 0.5\ eN_o\overline{V}/4$. This is half of the value of the upper limit predicted by (1) in the low pressure case. Thus, if j_z is given by (5) for $N_oR \ll 1/Q_{tr}$, it is expected that

$$j_z = 0.25\ eN_o(kT_o/2\pi m_e)^{1/2} \qquad (6)$$

for $N_oR \gg 1/Q_{tr}$.

In mercury the experimental values of j_zR show a marked deviation from equation (5) for $N_oR \approx 1/Q_{tr} \approx 10^{14}\ cm^{-2}$, and they tend to follow equation (6) with increasing N_oR However, the experiments do not cover sufficiently large N_oR-values to allow a detailed comparison.

For argon most of the expermental results cover the high pressure branch, and they show a satisfactory agreement with equation (6). There is an indication of a transition to equation (5), too, for $N_oR \simeq 10^{14}\ cm^{-2}$. Due to the high current densities a considerable heating of the neutral gas takes place in this case, and any experimental test of (6) requires a knowledge of T_o which will vary with j_zR. The value used by Lüthi and Seelig seems to refer to the positive column. T_o should rather be determined by the temperature in the cathode vessel which may differ from the column temperature. Therefore further investigations may be necessary before a detailed comparison can be made.

Lüthi and Seelig interpreted the high pressure branch in terms of another equation stating that the ion flux to the positive column tube wall is equal to the neutral flux returned at the current limit. As has been shown here, equation (6) offers an alternative explanation which I think is preferable for the following reason. Experiments in mercury arcs (e.g. Torvén 1968) have shown that walls can have a dominating influence on transient phenomena in pulsed current arcs. This is due to the long time constants associated with the change of the number of absorbed atoms at the surface which occurs when the ion flux to the wall is changed. In the above mentioned experiments mass equilibrium was attained after a time interval varying from a few seconds up to at most some ten seconds. However, to explain how a limitation of j_i can be brought about by the confining tube wall in a stationary discharge, one must find arguments showing that mass equilibrium cannot be attained within any reasonable time interval. It seems difficult to find such arguments unless the wall temperature is so low that the gas condenses on the wall. This case is, however, not of interest for ion laser discharges.

The results presented here suggest that both the low and high pressure branches of the current density limits can be explained by the same theoretical equation. It has also been shown that a current limitation model based on the saturation of the ion current at a double layer agrees well with available experimental data and known properties of a double layer. This makes it likely that this model is the basic current limitation mechanism in low pressure arcs, and it is expected that the rapidly increasing number of investigations of ion laser discharges will give a conclusive evidence of this.

References

Andersson D, Babić M, Sandahl S and Torvén S 1969 Proc. 9th Int. Conf. on Phenomena in Ionized Gases (Bucharest: Akad. Rep. Soc. Rom.) p 142

Andersson D 1977 J. Phys. D: Appl. Phys. 10, in the press

Andrews J G and Allen J E 1971 Proc Roy. Soc. Lond. A 320 459-72

Crawford F W and Freeston I L 1963 Proc. 6th Int. Conf. on Phenomena in Ionized Gases (Paris: EURATOM-CEA) Tome I p 461

Crawford F W and Cannara A B 1965 J. Appl. Phys. 36 3135-41

Langmuir I 1929 Phys. Rev. 33 954

Lüthi H R and Seelig W 1977 J. Appl. Phys. 48, in the press

Massey H S and Gilbody H B 1974 Electronic and Ionic Impact Phenomena (Oxford: Clarendon Press) 4 2772

Sandahl S 1971 Physica Scripta 3 275-8

Torvén S 1968 Arkiv för Fysik 35 513-26

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A theory for current limitation in ion laser discharges is investigated. The basic mechanism considered is saturation of the positive ion flux at an electric double layer by the limited flux of neutral atoms. The result is compared with a recently published synthesis of a large number of experimental data which agree well with those predicted by the double layer model.

Key words: Ion laser discharge, Double layer, Current limitation