ELECTRON ENERGY LOSS AT COLLISION IN CURRENT-MAINTAINED PLASMAS*

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In an important class of laboratory plasmas, the plasma is maintained in existence by the passage of a steady direct current through it. Energy taken from the electric field which drives the current maintains the ionization in the plasma against losses of charged particles by diffusion or recombination. This energy is initially supplied chiefly to the electrons, which can drift rapidly in the field, and the majority of it is ultimately transferred to the heavy plasma particles by means of electron–heavy-particle interactions. In the steady state the energy input to the plasma from the field is balanced by the energy lost from the plasma by various means, including radiation, thermal conduction and the diffusive transport of ionization, excitation, and dissociation energy. Such current-maintained plasmas may exist under a very wide range of conditions with variations of the order of ten decades each in pressure, current density, and ionization density.

It is well known that many such plasmas fall into one or other of two subclasses, called glow and arc plasmas, and that a transition, which is often discontinuous, may be achieved from the glow to the arc plasma by sufficiently increasing the pressure or the current density or both. Such a transition is often associated with a contraction of the plasma away from the walls of any containing vessel.

The properties of glow and arc plasmas are moderately well understood and, in many cases, such plasmas may be the subject of a satisfactory detailed analysis. It is the purpose of this note to show how the existence of two distinct types of current-maintained plasmas may be inferred from inspection of a plot of measurements of electron density against current density for a variety of discharges and how some of their salient features may be deduced in a very simple manner with the help of some elementary theory. Such a plot also shows clearly that the nature of the energy transfer between electrons and heavy particles is a very important feature of the plasma and that it is one of the most satisfactory criteria for use in classifying discharge plasmas.

Consider a simple model of a uniform plasma in which the electron density is n, the current density is j, and the conductivity of the plasma is σ. We may neglect the motion of positive ions in the electric field and assume that all the conductivity is due to the motion of electrons. Suppose that we think of the electron–heavy-particle interactions in terms of binary collisions with a collision frequency ν, and let the mean energy transferred from an electron to a heavy particle at collision be ΔU.

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The rate of energy input per unit volume is j^2/σ, and, if we assume that in the steady state all this energy is transferred from electrons to heavy particles at collisions, we have

$$j^2/\sigma = n\nu\Delta U. \tag{1}$$

We may write approximately

$$\sigma = ne^2/m\nu, \tag{2}$$

which, on substitution in (1), gives

$$j^2/n^2 = (e^2/m)\Delta U. \tag{3}$$

Consequently, a knowledge of j/n gives ΔU, and it is of interest to plot log n against log j for a range of current-maintained plasmas. This has been done in Figure 1. It will be seen that the set of points on the diagram has a lower boundary given approximately by the line corresponding to $\Delta U = 0 \cdot 2$ eV, and that the points numbered 1 to 7 lie close to this line. (The maximum deviation of any of these points from the line corresponds to a factor of about three in energy.) These points correspond to discharges in mercury, argon, and sodium at pressures below about $0 \cdot 003$ mmHg and the condition $\Delta U \sim 0 \cdot 2$ eV which they satisfy may be taken to be characteristic of the low pressure glow column. It may be noted that the current densities corresponding to these discharges are spread over about four decades. Clearly, an average energy $\sim 0 \cdot 2$ eV cannot be transferred by elastic collisions. The average fractional energy transfer at elastic collisions between electrons of mass m and temperature T_e and heavy particles of mass M and temperature T is given by

$$\Delta U/U = (2m/M)(1-T/T_e). \tag{4}$$

In typical laboratory current-maintained plasmas U cannot exceed a few electron volts, and, since $2m/M$ ranges from $\sim 10^{-4}$ for sodium to $\sim 10^{-5}$ for mercury, the average energy transfer at elastic collisions will be less than 10^{-3} eV, so that, in order to achieve an average transfer of $0 \cdot 2$ eV, virtually all the energy must be transferred at *inelastic* collisions. In such collisions most of the energy transferred is ultimately lost to the system without contributing to heating the gas.

The points on the j,n diagram also have an upper boundary, given approximately by the line corresponding to $\Delta U = 10^{-7}$ eV, and all the points numbered 12 to 19 lie close to this line, the maximum deviation corresponding to a factor of about four in energy. These points represent discharges in mercury, argon, sodium, neon, hydrogen, and the mixed gases of the carbon arc, at pressures between 20 mmHg and 140 atm, and they cover a range of current densities of more than six decades. The condition $\Delta U \sim 10^{-7}$ eV may be taken as characteristic of the arc column, and it is clear, from equation (4), that not only can such an amount of energy readily be transferred by elastic collisions, but that also, for the transfer to be so small, T must be approximately equal to T_e, so that the electron and heavy particle temperatures must be almost equal, and the arc plasma must be hot.

It is of interest to look at transitions from the glow to the arc column. The beginning of such a transition, with increasing pressure at constant current density,

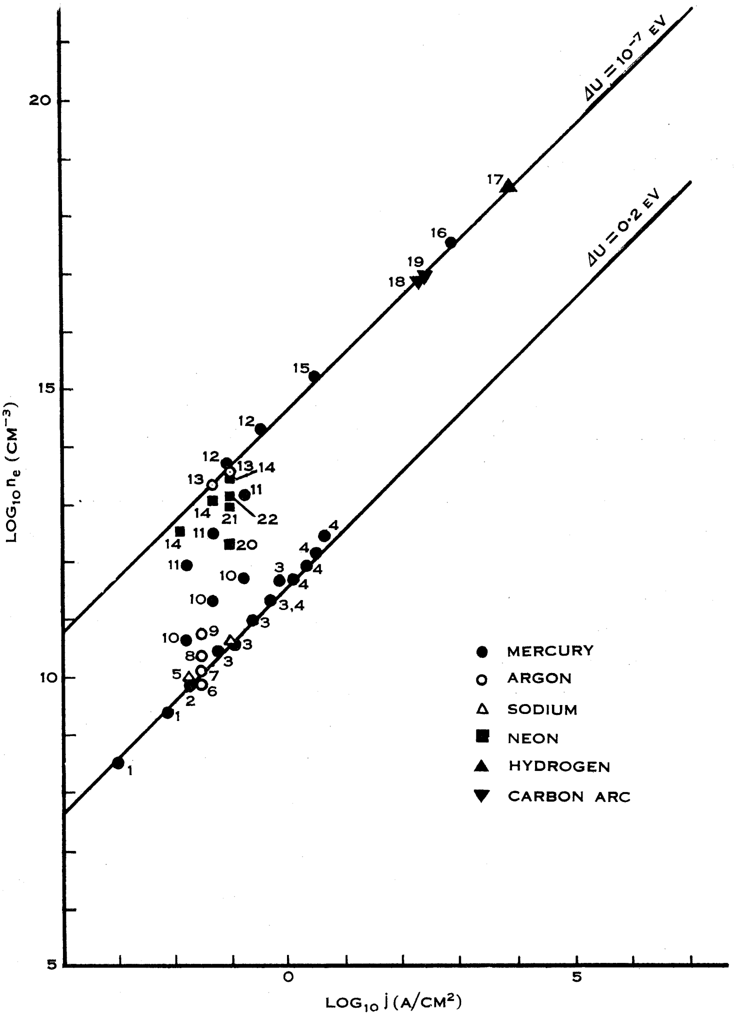

Fig. 1.—Double logarithmic plot of electron density n_e against current density j for a variety of current-maintained plasmas. The gases are indicated by the symbols marking the points. The gas pressures and the sources of the data are indicated by the numbers beside the points, as follows:

1. 0·0016 mmHg (Tonks 1931),
2. 0·00025 mmHg (Tonks 1931),
3. 0·00075 mmHg (Langmuir and Mott-Smith 1924),
4. 0·001 mmHg (Thonemann and Cowhig 1951),
5. 0·002 mmHg (Druyvesteyn and Warmoltz 1934),
6. 0·0013 mmHg (Groos 1934),
7. 0·0031 mmHg (Groos 1934),
8. 0·021 mmHg (Groos 1934),
9. 0·50 mmHg (Groos 1934),
10. 0·10 mmHg (Zakharova *et al.* 1960),
11. 1·0 mmHg (Zakharova *et al.* 1960),
12. 10·0 mmHg (Zakharova *et al.* 1960),
13. 20·0 mmHg (Zakharova *et al.* 1960),
14. 20·0 mmHg (Zakharova *et al.* 1960),
15. 1·0 atm (Elenbaas 1951),
16. 35 atm (Weizel and Rompe 1949),
17. 140 atm (Nissen 1954),
18. 1·0 atm (Maecker 1953),
19. 1·0 atm (Jürgens 1952),
20. 1·0 mmHg (Zakharova *et al.* 1960),
21. 5·0 mmHg (Zakharova *et al.* 1960),
22. 10·0 mmHg (Zakharova *et al.* 1960).

is represented by the sequence of points 6, 7, 8, 9 in the figure, corresponding to discharges in argon at pressures of $0 \cdot 0013$, $0 \cdot 0031$, $0 \cdot 021$, and $0 \cdot 5$ mmHg respectively. ΔU changes by a factor of about 60 as one traverses this sequence. Until recently, available points in the transition region were restricted to a neighbourhood between $\Delta U \sim 0 \cdot 2$ eV and $\Delta U \sim 10^{-2}$ eV, but a study by Zakharova *et al.* (1960) gave a variety of points covering most of the transition range, for current densities between $0 \cdot 018$ and $0 \cdot 36$ A/cm^2, and some of the points in the figure are taken from their paper. For example, the points numbered 10, 11, and 12, corresponding to discharges in mercury at $0 \cdot 1$, $1 \cdot 0$, and 10 mmHg, cover the complete transition, and the sequence 20, 21, 22, and the point numbered 14 above them, corresponding to discharges in neon at pressures of 1, 5, 10, and 20 mmHg respectively, show a transition from midway between the glow and arc column conditions almost up to the arc condition. Zakharova *et al.* measured ionization density profiles across the discharge and found a noticeable contraction of the discharge as the pressure was increased from 1 to 20 mmHg. They obtained several similar sequences in neon and argon which exhibit the same general features.

All the observations of transitions available are those with increasing pressure at substantially constant current density. No measurements of j and n appear to have been made through a transition with increasing current density at constant pressure.

It should perhaps be mentioned that the approximate constancy of j/n for glow and arc columns implies the approximate constancy of the drift velocity W as well as of ΔU, and, in fact, $\Delta U = mW^2$. The values of W corresponding to $\Delta U \sim 0 \cdot 2$ eV and 10^{-7} eV are $\sim 1 \cdot 9 \times 10^7$ and $1 \cdot 3 \times 10^4$ cm/s respectively.

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