Two extreme cases may be considered, namely the case with a small cathode,

$$R_s \ll \alpha d, \qquad C_a \doteq (\alpha^{1.63}/9)(R_s/d)^{0.37}, \qquad C_a\alpha_a^{-2} \doteq \tfrac{1}{9}(R_s/\alpha d)^{0.37}, \tag{28.12}$$

and the case with a large cathode

$$R_s \gg \alpha d, \qquad C_a \doteq \tfrac{1}{9}(R_s/d)^2, \qquad C_a\alpha_a^{-2} \doteq \tfrac{1}{9}(R_s/\alpha d)^2. \tag{28.13}$$

With a small cathode the perveance is small, and a nearly conical beam shape is obtained outside the extraction aperture.

With a large cathode, a high perveance is obtained, and the space-charge effect is large in the extracted beam. This beam may be characterized by C_a and by a minimum radius R_m; if $\alpha_a > 0$, R_m is the minimum radius of the beam extrapolated behind the extraction electrode. For $R_s \gg \alpha d$, one has $R_m \approx R_s$.

It should be noted that there is an absolute limitation on the perveance C_a. The simple expression, Eq. (28.13), may be used for $2R_s \lesssim 0.2d$, which gives $C_a \lesssim 0.001$, but due to complicated effects of the extraction aperture, it is difficult to obtain a good beam quality when d/R_s is small. With an advanced design with a large, concave cathode, a perveance of about 0.1 may be reached.

When the extracted beam is projected into a drift region with potential V by a lens system, the perveance C of the final beam is given by

$$C = C_a(V_a/V)^{3/2}. \tag{28.14}$$

If the type $(\alpha, d/R_s)$ of the extraction system is chosen so that C_a has a given value, and if C is specified, then the extraction voltage V_a is given by

$$V_a = V(C/C_a)^{2/3}. \tag{28.15}$$

If, furthermore, it is specified that the emittance should be low, $\tau < \tau_c$, so that it is the space-charge effect which limits the focusing, the size of the extraction system is limited by the condition $R_s < R_c$, where R_c is given by Eq. (27.4). The beam with $\tau < \tau_c$ can be produced when $R_c < R_{s\,\min} = (I/\pi i_{\max})$ [Eq. (27.5)]. When C is higher than the highest obtainable C_a, it is seen that a design with a deceleration lens must be used so that the beam with a high perveance is produced by acceleration and deceleration.

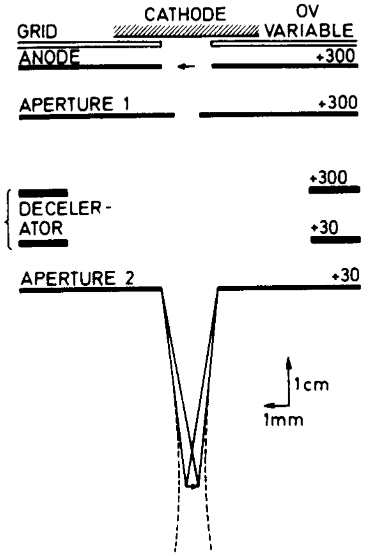


FIGURE 28.4[†]

A design of an electron gun of this type ($C > C_a$, $\tau < \tau_c$) is shown in Fig. 28.4. Here the extraction system has the structure of a plane triode, and the current is controlled by the grid voltage.

Finally the flat beam may be considered. Here the relations Eqs. (28.7) and (28.8) for the cylindrical diode may be used. For $\rho_c \ll d$, one has $I_1 = 2\alpha\rho_c H i_0 \doteq 2\alpha \cdot 0.8 i_0 d$, while I_1 for $\rho_a \ll d$ is given by $I_1 \doteq |2\alpha| 0.2 i_0 d$. Finite currents are obtained both for a beam which diverges from an infinitely narrow cathode and for a beam converging towards a very narrow extraction aperture.

For a concave cathode with $\rho_c < d$, the beam has a crossover at $z = \rho_c$ in the extraction gap, and the diode representation can be used for the region $0 \leqslant z \leqslant \rho_c$.

29. ION EXTRACTION

Ions may be produced in the plasma of a discharge in a gas at low pressure, and the ionization is here mainly due to electron-atom collisions and electron-molecule collisions. A beam of ions may be extracted from the discharge chamber through a small outlet opening.

[†] J. A. Simpson and C. E. Kuyatt, *Rev. Sci. Instrum.* **34**, 265 (1963).

There are many types of ion sources, but it is beyond the scope of this book to review this large and active field of research. Only a few general features of relevance to ion extraction may be mentioned.

For several elements in the periodic table, ions are formed directly from gases; for example, the ions N^+, N^{2+}, N_2^+ are produced in a discharge in N_2. Other elements are obtained from solid charge materials heated in an oven so that a suitable vapour pressure is obtained. For example K^+ ions can be produced in this way from KCl. In such cases, the temperature of the discharge chamber must be high so that a loss of charge material due to condensation on its walls is avoided. In some cases, a gaseous compound may be formed by chemical reactions; for example W^+ ions can be obtained from $WO_3 + CCl_4$, which gives the gaseous compound. By various techniques it is possible to produce ions of nearly all elements in the periodic table. Normally the extracted beam is a mixture of ions from several different elements, and therefore an ion accelerator consists of the ion source, the acceleration system, and a deflection magnet. When the magnet gives a large mass dispersion, isotopically pure beams are produced.

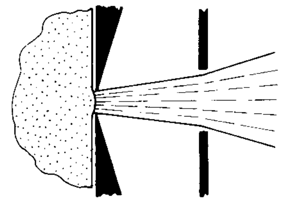
As mentioned above, charge material may be lost on the walls of the discharge chamber. Material is also lost by the flow through the outlet of nonionized atoms and molecules; here it is an important factor that a discharge can only be operated at pressures above a certain minimum, depending on the gas and the type of ion source, and the pressure should be kept close to this minimum. Furthermore, the degree of ionization should be high and the source outlet small. (A low minimum pressure is obtained by introducing a filament emitting electrons, and by introducing a magnetic field reducing the loss of electrons to side walls.)

The perveance of the extraction system is limited, and here it is noted that the perveance with different ions in the beam is derived from $\sum I_{M,n}(M/n)^{1/2}$. Therefore, a high abundance of the wanted type of ions is desirable; this abundance depends on the cleanliness of the chamber and on the parameters controlling the discharge.

The following features are of particular relevance for ion extraction.

The plasma is an equipotential region with equal densities of negative and positive charge. Its potential is close to (slightly lower than) the potential of the anode in the discharge chamber. When the plasma is facing an electrode with a lower potential, a quite well defined boundary surface is formed, and the current of positive ions to the electrode is

FIGURE 29.1



space-charge limited in the same way as the current in a diode. On the plasma boundary, the field strength is zero. The thickness of the diode layer increases with the potential difference.

An extraction system is shown in Fig. 29.1. From the plasma boundary across the outlet, the ions are extracted towards the extraction electrode which has the potential $-U$ with respect to the plasma potential. The shape of the plasma surface is determined by the condition that the space-charge limited current density outside the surface is determined by the product of ion density and ion velocity in the plasma. In the figure the plasma boundary is convex which, according to Section 28, corresponds to a high current density. If the plasma density and thus the current density is reduced, the boundary surface becomes concave. It is seen from Fig. 28.1 that rather small changes of the shape of the boundary surface correspond to large variations of the current density. However, under extreme conditions, the plasma boundary may become considerably deformed (Fig. 29.2), but such cases will not be considered here.

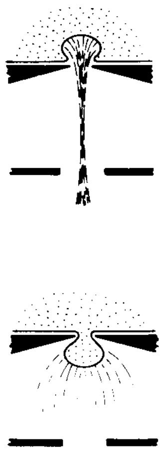


FIGURE 29.2

It is noted that the ion-source parameters, i.e., pressure, filament current, etc., affect the boundary curvature only through the resulting current density i. If two parameters are varied in such a way that i is kept constant, then the curvature of the boundary is constant. Thus, the cumulative parameter i can be considered as one of the extraction parameters.

Assume now that the outlet electrode and the extraction electrode are shaped in accordance with the Pierce geometry for a round, narrow beam with given values of R_s, d, and α (Section 28). Provided the current density is properly adjusted, this beam is produced, and all the relations derived in Section 28 for the round beam are valid. If the current density is not correct, the beam shape in the diode region is not conical, and the plasma boundary is not spherical; the relations obtained from the spherical diode are then not valid, and the beam quality is reduced.

Nevertheless, as established by Chavet and Bernas,† the representation by simple diode structures is approximately correct over the useful range of divergence for a beam from a very small outlet. Even though the beam shape is not exactly conical, the angle α at the source may be approximated as divergence at some distance from the outlet. The field distribution near the source is clearly dominated by the space charge field, since a very high current density is obtained in this region.

When the subsequent focusing system projects the beam as a convergent beam, and a small focus width is essential, there are several advantages obtained by extracting a divergent beam from a very small source outlet, $R_s \ll \alpha d$. The advantages are the following: (i) The beam quality is good, when the emittance is small. (ii) With a high current density at the outlet, one obtains a high ratio between the current and the loss of neutrals. (iii) The space-charge effect is small outside the extraction electrode.

On the other hand, the perveance is low, which means that a high extraction voltage must be applied for obtaining a given current. It is also noted that the divergent mode can only be used when a sufficiently dense plasma can be produced.

Chavet and Bernas performed an experimental investigation for the case of a flat beam, and they verified that with Pierce geometry for $\alpha = 0$, the cylindrical-diode representation could be applied for divergent beams and for nearly parallel beams, $R_s \gtrsim \alpha d$. For instance the model gives an approximately correct value of $dI/d\alpha$ for $\alpha = 0$.

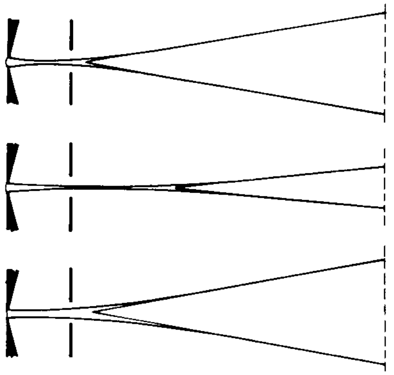


FIGURE 29.3

The case of a round beam was not investigated experimentally. Since the outer field has a stronger influence in this case, it may be expected that $dI/d\alpha$ for $\alpha = 0$ is smaller than predicted by the model. This implies that α may depend sensitively on the plasma density, which determines I.

In Fig. 29.3 it is illustrated that for $\alpha \approx 0$, small variations of α may give large variations of the position of the virtual source point to be imaged, and fluctuations of the plasma density may therefore reduce the beam quality. When R_s/d is not very small, the divergent mode of extraction can not be used, and stable running conditions are best obtained with a concave plasma boundary, which is obtained for a reduced current. It is thus seen that fluctuations of plasma density make it difficult to utilize a high perveance; other difficulties have been mentioned above.

It is concluded that for a specified current, the source outlet should be as small as possible, while the extraction length d should be large compared to R_s/α, which implies that the extraction voltage must be high. This conclusion applies when it is essential to obtain a small width of the final focus.

A different situation arises when a pencil beam should be produced, i.e., a narrow and nearly parallel beam. Here, a high brightness at $(x, x', y, y') = (0, 0, 0, 0)$ is essential for the final beam. This can best be obtained with a parallel or slightly convergent beam in the extraction region, and a narrow beam all the way throughout the acceleration system.

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† I. Chavet and R. Bernas, *Nucl. Instrum. Methods* **47**, 77 (1967).