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## Physical problems in high-intensity ion sources

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Three criteria are of great importance for high intensity ion sources:

1. the production of the ions in the discharge;
2. the transportation of the positive ions to the edge of the plasma, or out of the discharge in the direction of the exit opening;
3. the extraction of the ions from the source without disturbing the discharge.

We give a short discussion of these three points.

1. The gas in ion sources is usually ionized by electron impact. Call  $P_i$  the number of ions created per electron per unit path length and per unit of pressure at 0° C. Then the total number  $N_i$  of ions created per second is

$$N_i = i_e P_i p \bar{x}/e$$

where  $i_e$  is the electron current,  $p$  the pressure and  $\bar{x}$  the mean path length of an electron in the source.  $P_i$  shows a maximum at about 100 eV<sup>1</sup>). It is favourable to increase  $i_e$  and  $(p\bar{x})$  as much as possible. The factor  $(p\bar{x})$  is most interesting as, in order to avoid the use of big pumps, the pressure in the source must be reduced as much as possible to enable the extraction and acceleration of the ions. A theoretical expression for  $(p\bar{x})$  results from the following considerations.

Let us denote by  $P$  the probability for the disappearance of an electron from the discharge per unit path length.  $P$  will depend strongly on the type of ion source. In a first approximation it may be supposed however that in capillary arc sources (LAMAR) and in magnetic sources (FINKELSTEIN, HEIL).

$$P = P_a + P_c p$$

where  $P_a$  represents the loss of electrons to the anode and the walls independent of the pressure;  $P_c p$  represents the loss of electrons at pressure  $p$ , due to collisions with gas molecules. Both  $P_a$  and  $P_c$

are very sensitive to the velocity of the electrons and an applied magnetic field  $H$ . If  $H$  is parallel to the electric field, both  $P_a$  and  $P_c$  tend to decrease with increasing  $H$ . The same expression for  $P$  may hold approximately in high tension ion sources if  $\bar{x}$  is taken along the electron path. According to our definition of  $P$  we have:

$$i_e = i_{e,0} e^{-Px}$$

and

$$(p\bar{x}) = p \int_0^{\infty} P e^{-Px} x dx$$

or

$$(p\bar{x}) = \frac{p}{P} = \frac{p}{P_a + P_c p}.$$

As the recombination coefficient is certainly smaller than  $10^{-10}$  it can be easily shown that in our case the number of electrons lost by recombination is much smaller than the number of electrons present.

We distinguish between:

a) Capillary-arc ion sources and to some extent also high tension ion sources. Usually  $p \leq 10^{-1}$  mm Hg. As the loss of almost all electrons is due to the electrode configuration  $P_a \gg P_c p$  and  $(p\bar{x}) \sim p/P_a$ . This means that  $N_i$  is linearly proportional with  $p$ .

b) Magnetic sources, with oscillating electrons. The pressure range  $p$  is  $10^{-5}$ – $10^{-2}$  mm Hg. If anode dimensions and  $p$  are chosen well  $P_a \ll P_c p$  and consequently  $(p\bar{x}) \sim 1/P_c$ . This means that  $N_i$  is pressure independent.

c) High frequency ion sources differ from the preceding types in several respects. The value of  $\bar{x}$  is always several times the size of the source if diffusion losses are reduced. The electron current  $i_e$  depends on the pressure, as all electrons originate from the gas by ionisation;  $i_e$  is maximum if the electron collision frequency in the gas equals about the frequency  $\nu$  of the field. Consequently the optimum in  $p$  increases with  $\nu$ . A frequency of 100 M.C. corresponds with about  $p = 3 \cdot 10^{-2}$  mm Hg.

The sources of type *b* seem to be very convenient to obtain high values of  $N_i$  at low pressures. The electron current  $i_e$  can be made high and  $(p\bar{x})$  can be raised considerably by increasing  $H$ .

2. The maximum current which can be drawn from a source depends on the potential distribution and degree of ionisation in the plasma or discharge as well as on the extraction conditions. The ion

currents obtain their maximum value if they are so called "space charge limited". The minimum ion density  $n_{\min}^*$  at the emitting aequipotential surface, which we will call the "virtual cathode" of the ion source, giving rise to space charge limited currents, follows according to LANGMUIR<sup>2)</sup> from

$$\alpha n_{\min}^* \bar{v}^* e O = 5,4 \cdot 10^{-8} \frac{O}{d^2} \left( \frac{V^3}{M} \right)^{1/2}$$

where  $\bar{v}^*$  is the mean velocity of the ions at the virtual cathode; this is the aequipotential surface at which the electrons are reflected back into the discharge. This surface is situated approximately at B in Fig. 1. The factor  $\alpha$  is about 0.25 for thermal ions and 1 for

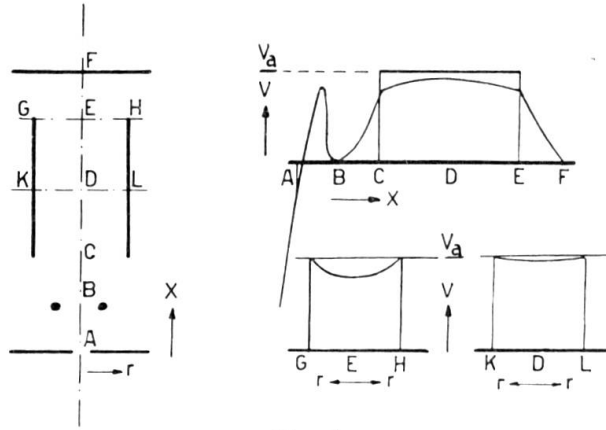


Fig. 1.

Scheme of the potential distribution in a magnetic ion source with coaxial magnetic field. Direction of ion extraction and magnetic field coincide.

- a) The source with electrodes;
- b) axial potential distribution for space charge limited ion currents;
- c) radial potential distributions.

perfect unidirectional ions.  $O$  is the area of the virtual cathode,  $d$  its distance from the extraction electrode,  $V$  the extraction voltage in Volts and  $M$  the mass number of the ions.

In order to obtain space charge limited ion currents with an ion density  $n_{\min}^*$  as small as possible, one must realize:

a)  $\bar{v}^*$  as large as possible; increase from thermal velocity (0,1 eV) to 100 eV increases  $\bar{v}^*$  already with a factor thirty.

b)  $\alpha = 1$ , which means unidirectional ions.

c) the depth of the source, from which the unidirectional ions are transported to the virtual cathode as large as possible. To a certain extent the number of ions is proportional with this depth.

The ion density  $n_{\min}$  in the ion production region ( $CD$  in Fig. 1) of the plasma is related with  $n_{\min}^*$  by

$$n_{\min} \bar{v} = n_{\min}^* \bar{v}^*$$

if  $\bar{v}$  is the mean velocity of the ions in the plasma.

We touch here one of the most fundamental problems, *viz.* how to transport the ions from the production zone in the source to the emitting equipotential surface, without losing them to all directions. A good source is self focussing. The potential distribution forces the positive ions to the emitting surface. In this case there

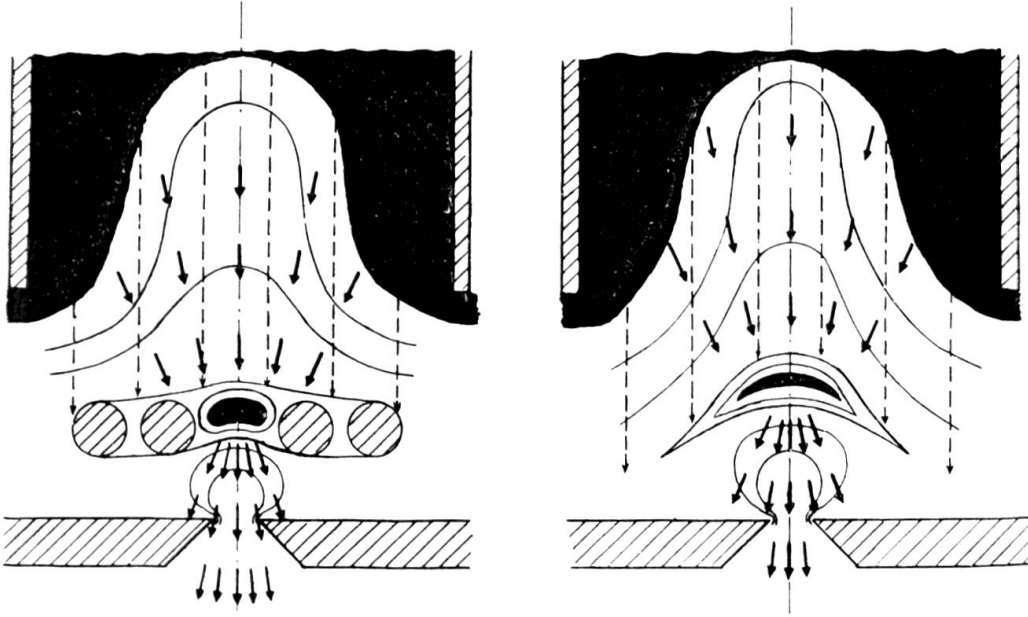


Fig. 2.

Comparison between the extraction mechanism for space charge limited ion currents in a magnetic ion source with a filament at the extraction side (grid functioning) and the usual FINKELSTEIN type. The drawn lines indicate the electric equipotential surfaces; the block lines indicate the electron oscillation paths. The arrows give the paths of the positive ions. Black regions are regions with a potential which is relatively high, approx. anode potential.

will be a potential trough, as there is *e. g.* in the magnetic ion source of the FINKELSTEIN type, Fig. 1, and also in the high tension sources. A bad source has a potential mountain in the production zone, which gives a diverging ion beam in the plasma itself. This can happen in a capillary arc source.

3. The space charge limited current indicated in 2. holds for a plane emitter. However the "penetrating" field of the strongly negative extraction potential displaces and curves the ion emitting surface, which induces a resemblance with Langmuir's external

emitter. It also results in an increase of  $d$ . In this way an increasing high tension field partially eliminates its favourable action ( $V^{3/2}$ ) by the increase of  $d$ , but especially by a deformation of the ion emitting surface. The latter effect can easily reduce the maximum ion currents with a factor 4.

These facts are of great influence in high tension type ion sources, and also in some high frequency types, if the discharge is not intense. No doubt also in the Lamar-type capillary-arc ion source and in the Heil-type magnetic source some influence remains, but there

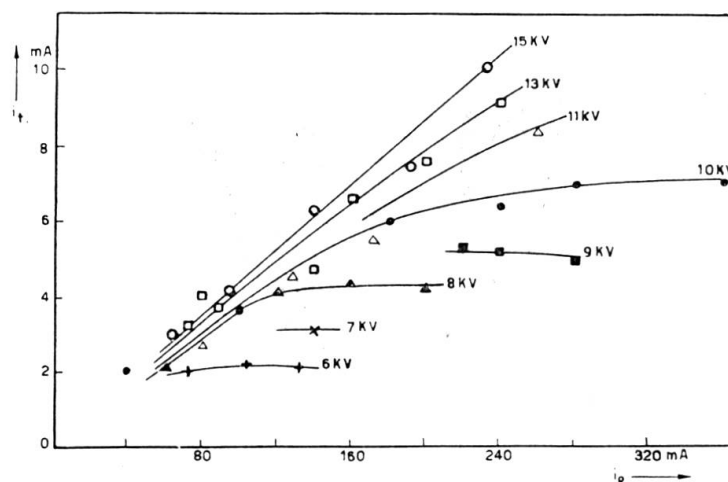


Fig. 3.

The ion current on the target ( $i_t$ ) as a function of the emission current of the filament  $i_e$ , for helium gas. The accelerating tensions vary from 6 to 15 kV.

it must be kept small in order to prevent extinguishing the discharge. From these points of view it follows that for the latter two types the presence of a grid over the extraction opening might be favourable. The influence one can observe in Fig. 2.

As a consequence of the facts mentioned sub 1, 2 and 3 we constructed a magnetic ion source in Amsterdam<sup>3)</sup> producing typically sp. ch. lim. ion currents of the order of 5 mA, at a gas pressure in the source of  $4 \cdot 10^{-4}$  mm Hg. The number of accelerated ions leaving the source, was about 80% of the total number of gas molecules consumed. We used  $H_2$ , He and  $N_2$  gas. The beam was not yet analyzed. The typical space charge limited ion currents are shown in Fig. 3.

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