Zeitschrift: Helvetica Physica Acta

Band: 23 (1950)

Heft: [3]: Supplementum 3. Internationaler Kongress über Kernphysik und Quantenelektrodynamik

Artikel: Radiofrequency ion sources

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DOI: https://doi.org/10.5169/seals-422259

Radiofrequency Ion Sources.

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Summary. This paper reviews the published data on R. F. type ion sources. Various sources are compared, and factors influencing the design and performance of these sources are discussed.

Introduction.

Recently an article has appeared in Nucleonics[1]) reviewing the various types of positive ion sources developed for use with high voltage equipment. Radio-frequency ion sources (R. F. sources) are mentioned briefly in this article; I propose to review in this paper the data which has been published on this type of source and to consider the factors which influence its design and performance.

Desirable properties of positive-ion sources are well known; high proton percentage, low energy spread, large beam currents and low gas consumption, simplicity of construction and operation, long life and reliability of operation, low power consumption, are of varying importance depending on the particular requirements of the accelerating equipment. The R. F. source compares very favourably with earlier types on the basis of such requirements.

Historically, the first reported attempt to use radiofrequency excitation of a gas discharge for this purpose is mentioned by GETTING[2]) in 1941. His attempt was apparently not very successfull, and the first indication of the possibilities of this type of ion source was indicated by THONEMANN[3]), who described some preliminary work carried out at the University of Sidney, Australia.

Independently, D. ROAF, now at the Clarendon Laboratory, Oxford, started work on the use of an R. F. ion source at Chalk River Laboratory in Canada and I fell heir to his equipment when he returned to England. Four papers describing the successful development of R. F. ion sources have appeared in the literature and many such sources have been built and operated. There are for instance six such sources in use at the Clarendon Laboratory in Oxford, two at A.E.R.E., Harwell, one at Durham University, two or more in Cambridge, and many others.

Much of the material presented in this article is common knowledge amongst those who have used and operated these sources. A

detailed account of much careful work by THONEMANN[4]) on the development of a radiofrequency ion source is contained in his D. Ph. thesis, and I have had the benefit of several discussions with THONEMANN and his collaborators at the Clarendon Laboratory.

Description of Sources.

Figs. 1—8 have been taken from the published papers on radiofrequency ion sources. Fig. 1 shows the original source described by THONEMANN[3]). It consists of a two litre pyrex flask, two external electrodes for exciting an R. F. discharge in the flask, an extracting

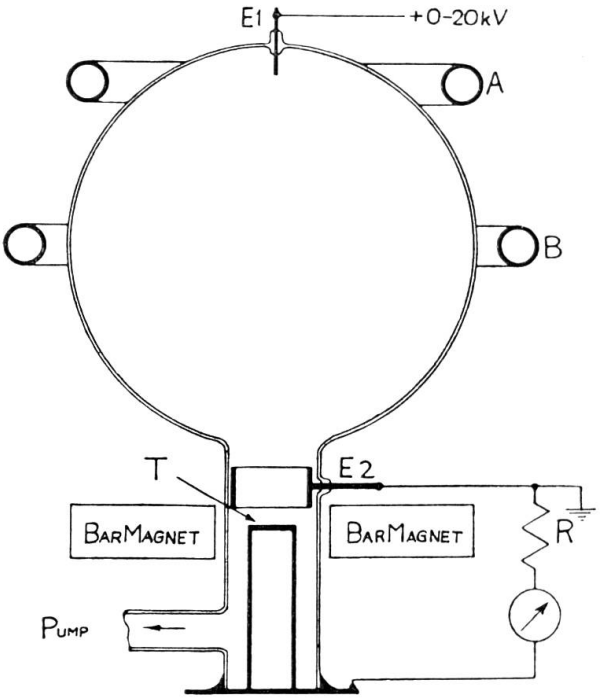

Fig. 1.

electrode and target located in the neck of the flask. THONEMANN described the formation of a concave boundary to the plasma, near the negative electrode, which moved away from the electrode as the extracting voltage was increased. Currents of the order of 10 ma with 10 k. v. applied voltage were obtained; the arrangement of electrodes produced a well focussed beam at the target but the beam was not brought out of the discharge tube.

Fig. 2 shows the source which Bayly and myself[5]) developed at Chalk River. It bears a close resemblance to the THONEMANN source. In this source the bottle used is smaller and some care has been

taken to reduce the metal area exposed to the discharge. The discharge is excited by a coil to obtain the more intense type of ring discharge, and electrodes 1, 2, and 3 (Fig. 2) are used for extracting, and initial focussing of the ion beam. Fig. 3 shows the electrode assembly in more detail. Beam currents of about 500 μamp. were obtained, containing $\sim$ 50% protons and the gas flow rate was $\sim$ 15 cc/hr. About 250 watts of R. F. power were used at 15 Mc/s frequency.

Fig. 4 shows the source developed at Glasgow University by Rutherglen and Cole[6]) at approximately the same time. In this

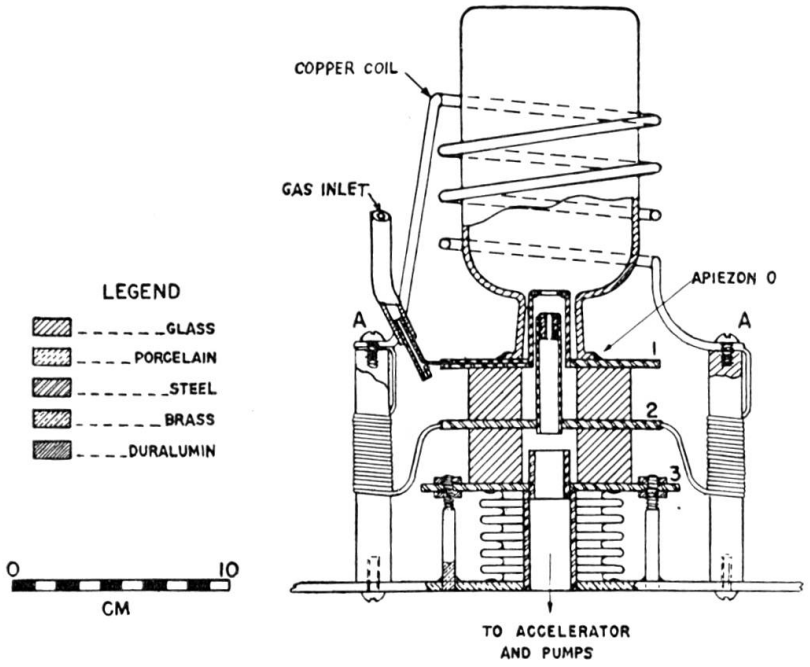

Fig. 2.
Improved model of the radio-frequency type ion source.

source electrostatic excitation of the discharge is used, with two external electrodes and the discharge vessel is smaller than in the previous figure. Great care has been taken to reduce the metal surface exposed to the discharge and an axial magnetic field is used to increase the intensity of the discharge. Only 30 watts of R. F. power at 180 Mc/sec. were used, and the performance data of the source are much the same as that of Fig. 2.

Fig. 5 shows the R. F. source developed by R. N. Hall[7]) working at the California Institute of Technology. This source uses a very small pyrex or quartz discharge chamber, but operates at a pressure of $\sim$ 5 times higher than that in the previous sources. A

high frequency, 450 Mc/sec, is used to excite the discharge and the oscillator delivers $\sim$ 60 watts output power. Again an axial magnetic field is used. The ions are allowed to diffuse out of the source before acceleration, and Fig. 6 shows an enlarged view of the discharge chamber and outlet hole. There is some difference of opinion

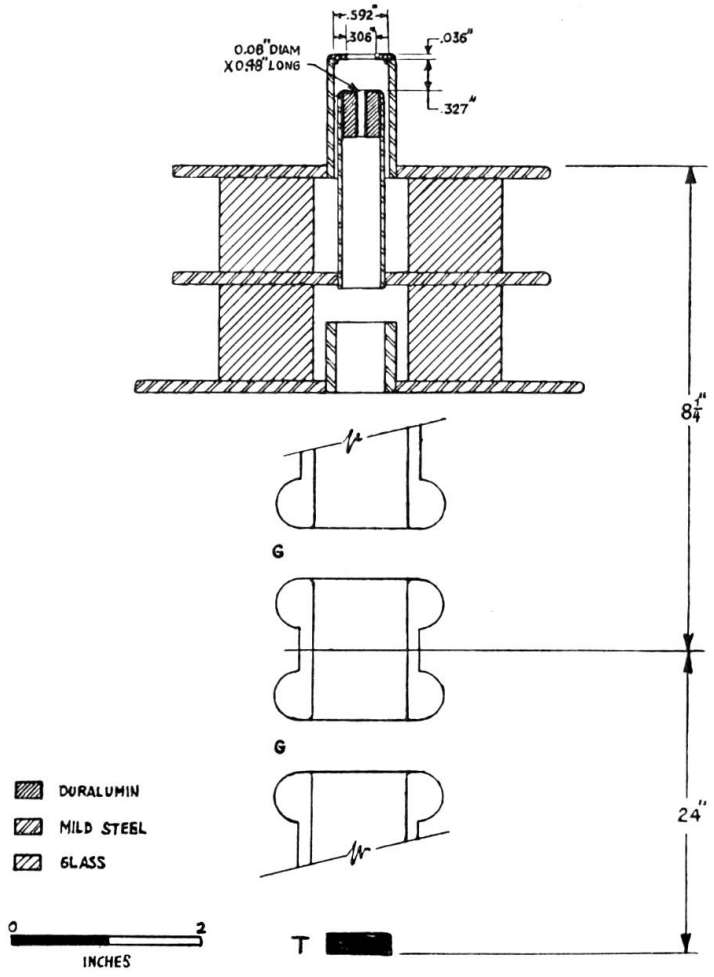

Fig. 3.
Arrangement of the ion source electrode assembly, the main accelerating gapi, G, G, and the target, T.

as to the merits of probe type extraction as compared with diffusion, the contention being that probe extraction increases the energy spread of the ions in the beam from the source. This point will be mentioned again. This source again gave ion currents $\sim$ 400 μamp. containing $\sim$ 60% protons and used 30 cc hydrogen per hour.

Fig. 7 shows the R. F. source developed by THONEMANN and his collaborators[8]) at the Clarendon laboratory. Proton currents of the

order of 500 μamp., with a gas consumption of 15 cc/hr. are obtained. Since this particular design of source has had widespread use, and its properties have been investigated carefully, it is considered in more detail. The pyrex discharge tube had been designed so that the metal exposed to the discharge is a minimum, and the extracting electrode projects into the centre of the discharge in the belief that the centre of the discharge, away from the walls, contains a higher percentage of atomic ions. Critical design points are the necessity

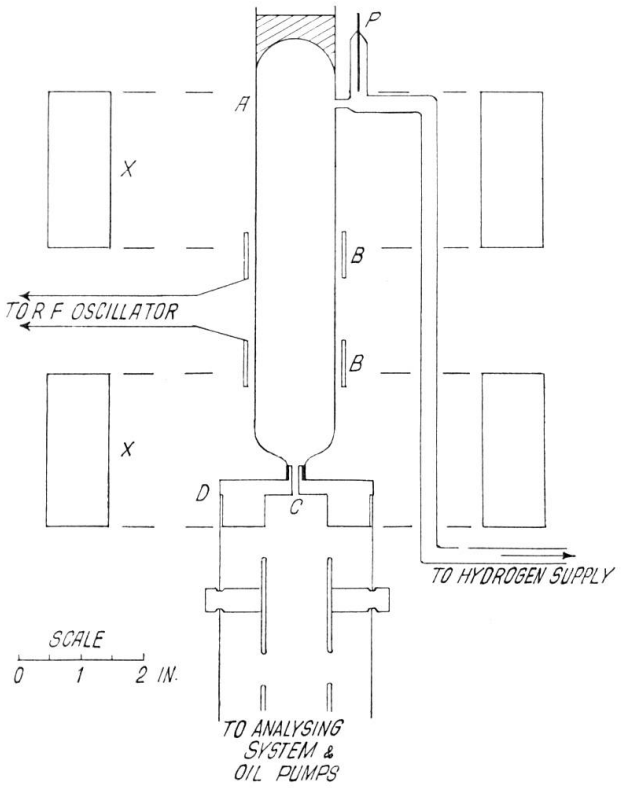

Fig. 4.

of having the glass sleeve surrounding the extracting electrode accurately concentric with it, and with its top surface carefully flattened.

Tables 1–3 gives the results of magnetic analysis of the beam from this source, using deuterium with about 7% hydrogen, and working under optimum conditions. These results are very good indeed. The variation of the atomic ion percentage with pressure in the discharge is also shown, and it can be seen that the pressure in the source is not a critical variable. THONEMANN[4]) has also investigated the effect of an axial magnetic field and has found that at a frequency of 20 Mc/sec. the magnetic field only improved the source performance

at very low power inputs. On the basis of the results given, there is of course little room for improvement of atomic ion percentage through the use of a magnetic field.

Fig. 8 shows the results of measurements of the energy spread of the ion beam from this source; the experimental curve is compared with that calculated from the constants of the analyser. These results, taken with probe type extraction, show that this method of extraction does not introduce an energy spread of the order of magnitude of the extracting voltage, and it is probable that there is

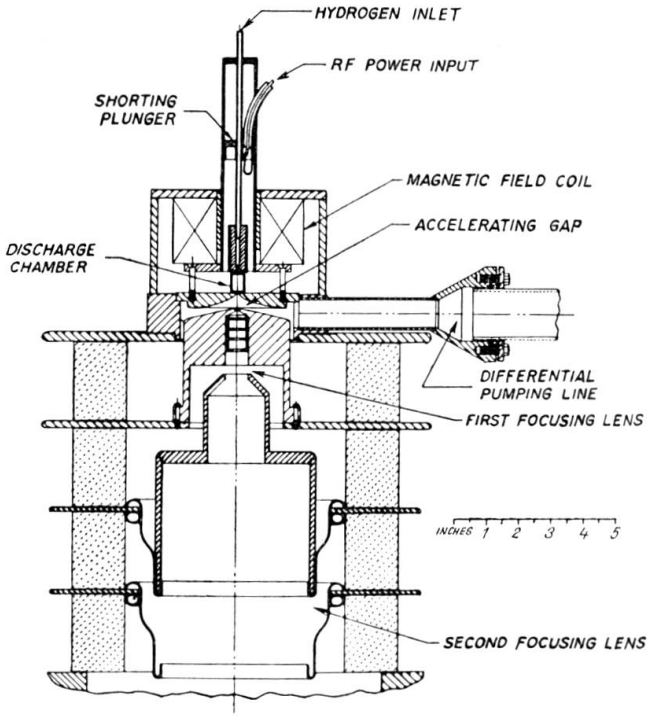

Fig. 5.
Radiofrequency ion source and accelerating electrode system.

little to choose between probe type of extraction and diffusion from the source as far as energy spread in the beam is concerned. On the other hand, probe type extraction should always improve the ratio of beam current to gas flow.

Production of Atomic Hydrogen.

Let us now consider in more detail some of the factors governing the production of beams containing a high percentage of protons. Conditions in the discharge tube must be favourable to the production of a high partial pressure of atomic hydrogen. The cross-section

for the production of protons by electron collision with a hydrogen molecule is not an important factor, since most of the ionizing collisions produce singly ionized molecules[9]). It seems reasonable to suppose that atomic hydrogen is produced as a primary reaction. The lifetime of atomic hydrogen in the discharge tube is such that the partial pressure of atomic hydrogen builds up and the protons are formed by ionization of this atomic hydrogen. Recombination of atomic hydrogen on the pyrex surface of the discharge vessel is sufficiently slow to allow this condition to be reached. Recombination of the atomic hydrogen by a three body collision in the gas is probably negligible at these pressures.

In a recent paper by G. I. Finch[10]), the following statement appears. "These experiments... show that dry hydrogen is not dis-

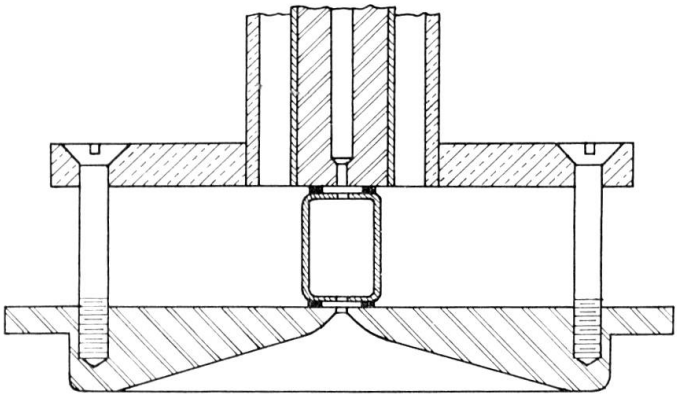

Fig. 6.
Details of ion source construction. The vacuum seal at each end of the discharge chamber is provided by two gaskets made of 0.018-in. fuse-wire.

sociated by the discharge, and that the minute amount of atomic hydrogen formed is attributable to that trace of moisture which can hardly be eliminated in an experiment of this kind carried out in an apparatus equipped with barometric mercury cut-offs." The experiments referred to deal with the excitation of an R. F. discharge using $\sim$ 150 watts at 26 Mc/s, at a pressure of about 30 microns. The glass discharge vessel was $\sim$ 10 cms. diameter and the hydrogen carefully purified. I mention this statement since it is apparently in direct contradiction to the results of experiments on R. F. discharges mentioned above. In the experiments at the Clarendon Laboratory, for instance, the hydrogen was introduced through a palladium leak and the spectrum of the discharge showed almost pure Balmer lines, with very little trace of the molecular spectra.

Extraction of Positive Ion Beam.

In most of the experimental arrangements discussed previously the ions are extracted from the discharge by a probe. The geometry is chosen so that a reasonable fraction of the ion current extracted from the discharge passes through the small hole in the extraction

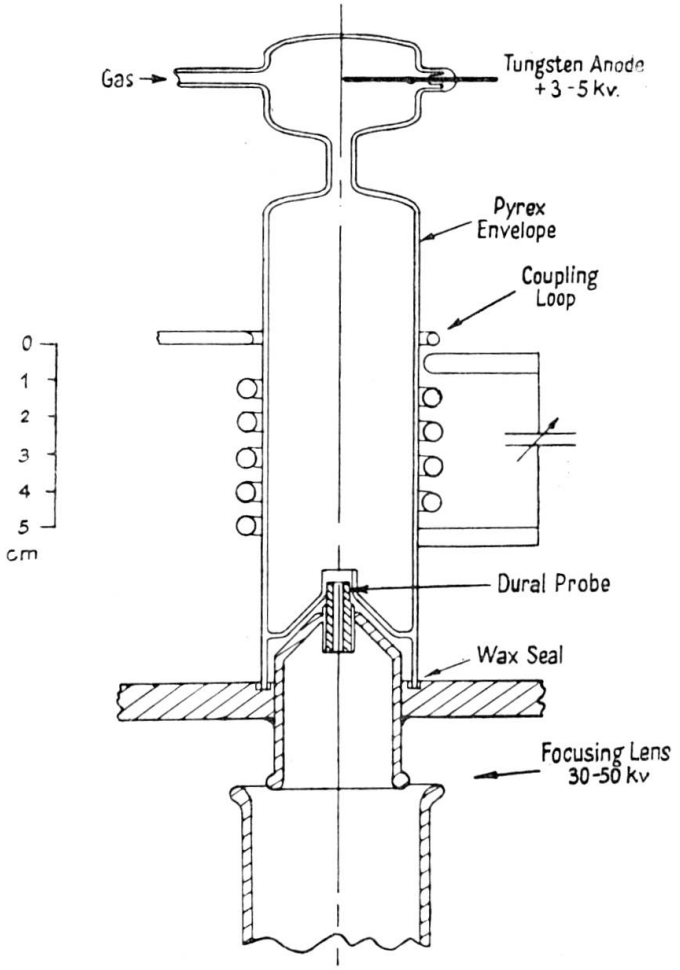

Fig. 7.
Assembly of the radio-frequency ion source.

electrode and emerges in a beam. The ratio of protons to emergent gas atoms or molecules is of the order of 1 or 2%, a value which is higher than that achieved in most of the earlier ion sources.

The optimum design of the extracting electrode arrangement is of major importance in the performance of the ion-source; further work on this problem would probably lead to marked improvement in the performance of this type of source. Qualitative arguments leading to the choice of canal dimensions are as follows: the beam

emerging from the ion source is usually subjected to further acceleration and focussing by an electrostatic lens system. For a voltage ratio on the first lens of the order of 10, the canal is usually located 2 or 3 lens diameters back from the centre of the first lens in order to form a real image. To avoid serious spherical aberration in the lens, the beam is allowed to fill about half the lens diameter. These

Table 1.

The mass spectrum of a deuterium ion beam.

Magnet current (ma.)	Species	Percentage abundance
29	D_1^+ from dissociation of D_3^+	0.9
32	H_1^+; D_1^+ from dissociation of D_2^+	6.0
54	D_1^+ and H_2^+	79.0
60	D_2^+ from dissociation of D_3^+	1.0
62	HD^+ and H_3^+	0.9
80	D_2^+ and H_2D^+	8.8
90	HD_2^+	1.4
99	D_3^+	2.1

Table 2.

Pressure (microns)		14	16	18	20	23	25	26	28
Percentage abundance	(H_1^+	84	85	88	89	90	90	92	91
	(H_2^+	14	11	10	8	7	8	5	6
	(H_3^+	2	4	2	3	3	2	3	3

Table 3.

Pressure (microns)		13	15	17	20	22	25	28	30
Percentage abundance	(D_1^+	72	73	85	85	84	89	87	87
	(D_2^+	23	20	13	11	12	8	8	8
	(D_2^+	5	7	2	4	4	3	5	5

considerations lead to a choice of the ratio of canal length to diameter of the order of 10. The actual canal diameter is then chosen to give either the required beam current or the maximum allowable gas consumption, depending on which limit is first reached. The sources described previously use canals of the order of $^1/_{10}''$ diameter, and deliver ion beams of the order of 500 μamps.

The following figures taken from an experimental arrangement in use at the Clarendon laboratory give a good example of what can be achieved by subsequent focussing of the extracted ion beam. A deuteron beam emerges from the ion source through a canal $^3/_{32}''$

diameter and $^3/_4''$ long at a voltage of 3,5 k.v. It is then accelerated to 40 k.v. by an electrostatic lens arrangement and focussed through a second canal $^1/_8''$ diameter and 3″ long. A straight through type analyser (crossed electric and magnetic fields) is placed in front of the second canal. Emergent analysed deuteron beams of 180 μ a. have been obtained from the second canal. These represent preliminary results and may be improved by better alignment.

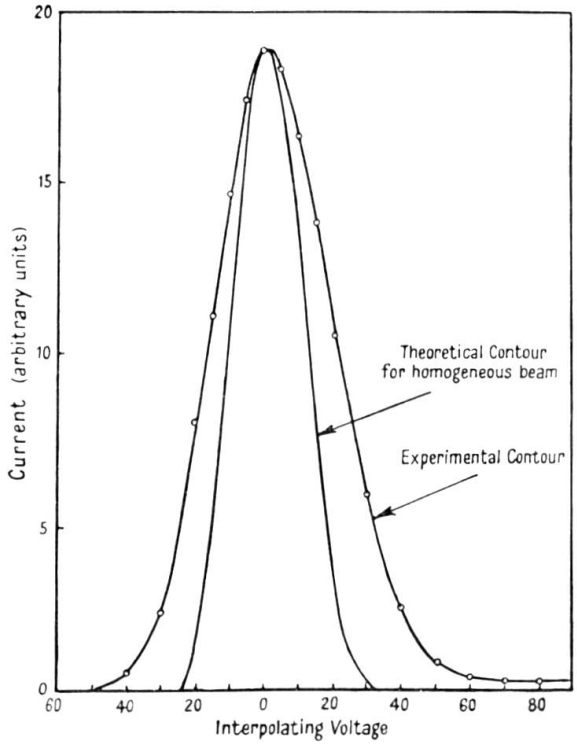

Fig. 8.
Comparison of the theoretical contour for a homogeneous beam with the D_1 ion contour.
$Vp = 3$ kv., $Va = 10$ kv., $p = 20\ \mu$; $s_1 = 0{\cdot}1$ mm; $s_2 = 0{\cdot}1$ mm.

The problem of arranging further focussing electrodes to deal with the emergent beam from an R. F. ion source can be calculated from the lens data available from the work on electron optics. The problem of designing the actual extracting electrode system is however complicated by two factors:

(1) The requirement that a minimum amount of metal surface be exposed to the R. F. discharge.

(2) The fact that the positive ion emitting surface is not well defined.

With the extracting electrode systems of the sources described previously the following behaviour is observed. The plasma potential remains close to that of the positive electrode, while near the

negative electrode a concave boundary is formed, relatively sharply defined, with a dark space in the region of the electrode. This boundary recedes from the negative electrode when the extracting voltage is increased, or the R. F. power is decreased. Apparently this boundary behaves as an emitter of positive ions, and adjusts its position so that space charge limited emission conditions prevail at the boundary. For any particular arrangement of the extracting electrodes, and a given value of the extracting potential, there is an optimum R. F. power, corresponding to best focussing of the positive ion beam through the canal.

The arrangement used with the Oxford type ion source has been investigated over a range of parameters such as the diameter of the extracting electrode, the diameter of the glass sleeve, and the location of the extracting electrode in the sleeve. The dimensions given in the published paper[8]) represent near optimum design for this particular arrangement. Calculations made by BEDFORD[11]) and THONEMANN[4]) show that the current focussed through the canal at a given extracting voltage is only 10 to 15% of the maximum possible at this voltage, if this maximum is set by the space charge repulsion of the beam. It would seem likely that further work on the design of extracting electrodes would considerably improve the performance of the ion source.

Reliability of Operation.

The behaviour of R. F. sources and the more common types of failure under conditions of frequent use are of some interest. The R. F. sources are not trouble free. Fortunately, the performance of the source, as far as proton percentage is concerned, can be reliably estimated from the colour of the R. F. discharge. When operating with a high proton percentage ($> 50\%$) the discharge is bright red and deterioration of performance is associated with colour change of the discharge, a pale pink colour indicating a proton percentage of the order of 25%. Air leaks in the hydrogen supply line produce similar changes. It is also advisable to have ample R. F. power available, particularly in initial testing of a source, since the problem of properly coupling the power into the discharge is complicated by the changing impedance of the discharge as the power is increased.

Our experience in Canada showed that the source would operate for many days, giving reproducible results. When first switched on the source often took 1 to 2 hours to reach optimum conditions. Occasionally, however, it was necessary to remove the discharge vessel and clean it (with hydrofluoric acid) before proper perfor-

mance could be obtained. Accidents at the target end of the equipment, e. g. breaking counter windows, usually resulted in poor subsequent source performance until the bottle was cleaned. These changes may be associated with the entrance of pump oil vapour in relatively large quantities while the source is running, or the effect of oxygen on the surfaces inside the discharge vessel. Some thin deposits are usually visible on the surface of a discharge vessel which has operated for some time. These occur on the walls at the end of the tube where the discharge is least intense, and do not necessarily seriously affect the proton percentage. They probably arise from metal sputtered off the extracting electrode by the ion bombardment. The extracting electrode is usually made of aluminium to reduce sputtering.

At Oxford the failure of a source is usually indicated by a sudden change in colour of the discharge from red to white. Sometimes the discharge regains its red colour after running for a short time, persistent refusal to return to the red colour is rectified by careful cleaning of the discharge tube. Some of the Oxford sources have operated for several weeks without attention. Another fault which occurs in sources which have operated for some time is difficulty in starting the discharge. This is easily remedied by use of a Tesla coil or similar device, or momentarily increasing the pressure.

Conclusion.

Many of these sources are now being used as more or less standard equipment in high voltage accelerating apparatus. Work is being done at Cambridge and at Harwell to adapt this type of source for work in pressure insulated electrostatic generators. I believe they are sufficiently robust, trouble free, and efficient to find increasing favour for use in almost all applications where Ion Sources are required.

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