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Abstract: Over the past 25 years many types of ion source have been developed for different applications, but here the presentation will focus on the magnetic multipole source, as it probably has the greatest physical simplicity and yet has the largest development potential. We describe the underlying physics of these sources and the processes leading to the production of high currents and current densities of the required ion species including the formation of negative ions. The use of these sources is also discussed in both fusion and particle accelerator research areas, together with potential future improvements.

### Introduction

The development of positive ion sources has a long history which has led to a large diversification of ion source types for the many functions they have to satisfy. Most of these applications, such as those for particle accelerators and most ion implantation sources, can be satisfied by low current sources where the beam can be extracted from a single small aperture. However it has become necessary to develop high current sources for neutral beam heating of plasmas in the fusion programme and also for some of the recent high ion mass implanters for the semiconductor industry. In the former case the beam current of 50-100 A of protons or deuterons per source has demanded radical developments in the ion source field.

The two basic elements of an ion source are the plasma generator and the accelerating column. The former determines the ion species (through the type of gas or vapour) and the ion flux density, while the latter transports this flux and accelerates it in the presence of its own space charge to the desired energy. The beam usually emerges from the column in a collimated state. In order to produce a high current ion beam both the above elements of the ion source have been subject to major development programmes in several laboratories, and some of these developments are described in this paper.

We begin the presentation with a discussion on the limits to beam extraction in the form of a single beamlet, in order to relate the development of the high current source to earlier work. It was this limitation which led to research into multiple extraction aperture columns to raise the total current above that set by a single aperture. The use of multiple aperture accelerators has led to significant improvements in plasma source design, which are also described in this paper, in particular plasma uniformity, ion production efficiency and gas utilisation, to meet the more stringent requirements of the accelerator. It is also advantageous to have one dominant ion species and usually discharge plasmas form several ion species from one gas. This problem has been solved in several cases to raise the desired ion species to between 80 and 100%of all ions extracted by modifications to the plasma generator.

#### Extraction of Ion Beams

Before discussing high current beams extracted from multiple apertures, it is useful to examine the beam current that can be accelerated through a single circular aperture. The simplest accelerator design uses only three electrodes (a triode accelerator), and is shown in Fig. 1. The high voltage electrode is adjacent to the plasma generator and often has a tapered profile, first proposed by Pierce [1], to reduce beam aberrations. The plasma boundary which emits the positive ions forms in this aperture and has a quasi-spherical shape. The second electrode is at a slightly negative potential relative to the earthy third electrode, and the fields of this second gap prevent a back-electron beam being accelerated to the plasma source from the dilute plasma in the beam channel downstream of the accelerator. If the background gas pressure is very low it may be possible to omit these fields, but the beam may then diverge strongly because of internal space charge.

The ion beam is accelerated to its full energy (in practice slightly above full energy) by the potential across the first gap. In some high voltage accelerators this gap is sub-divided for voltage hold-off reasons, and this can also confer an improvement to the minimum beam divergence through the additional control of the beam envelope in the accelerator [2].

In the limit of many such electrodes the accelerator tends to a Pierce column used in many Cockcroft-Walton systems. In the discussion which follows we limit the accelerator design to a single accelerating gap in order to derive the limiting beam current. Further post-acceleration in a multiple gap system will not increase this maximum current.

#### Extraction of a circular collimated beam

The equation governing the beam current that can be extracted across a single gap of length d (this length is longer than the metal-to-metal gap) across which a voltage V is applied was first derived by Langmuir and Blodgett [3]. In circular geometry, Holmes and Thompson [2] have expanded the equation for the extracted current, I, to a more convenient form which is:

$$I = \frac{4 \pi \epsilon}{9} \left(\frac{2e}{m_1}\right)^{\frac{1}{2}} \frac{3/2}{V} \cdot \frac{a^2}{a^2} \cdot (1 + 0.8k)^2$$
(1)

where  $k = d\varepsilon/a$ , a is the aperture radius and  $\Theta$  is the angle of divergence of the ray at the aperture edge.

In a triode accelerator, where the second gap deceleration potential is negligible in comparison with the first gap accelerating potential, we can describe the radius and divergence of the rays leaving the accelerator using the matrix method of ray tracing, and these are [3]:

$$r' = \frac{a}{d} \left(\frac{4}{3} - \frac{k}{3}\right) \tag{2}$$

$$\mathbf{r} = \mathbf{a}(\mathbf{1} + \mathbf{k}) \tag{3}$$

If the beam is collimated then k = -0.25. This corresponds to a slightly concave plasma boundary (as shown in Fig. 1) and becomes more concave for short extraction gaps or large values of a. If a/d approaches unity the paraxial ray limit is broken and the beam becomes aberrated, a condition known as the "anode hole" effect.

The dependence of r' on k leads to a beam divergence beam perveance curve of the type shown by Coupland [4]. If the beam is to be collimated then only minor excursions of the order of 5% are permitted from perveance matched beam current, which is defined by eliminating k in Eq. (1). Hence:

$$I = 0.28 \pi \epsilon_{0} \left(\frac{2e}{m_{1}}\right)^{\frac{1}{2}} \sqrt{\frac{3}{2}} \frac{a^{2}}{d^{2}}$$
(4)

Equation (4), however, also contains the ratio a/d, and experiments by Coupland et al [4] have shown that for triode accelerators a/d should not exceed 0.7 if aberrations are to be avoided. Slightly higher values of a/d are possible in multi-gap accelerators as k has a smaller value. Using this empirical value for a/d and rewriting Eq. (4) in terms of the ionic mass number, A, we have:

$$I \leq 5.36 \times 10^{-6} \frac{V^{3/2}}{A^{1/2}}$$
 [Amp] (5)

This current only depends on the extraction voltage and ion mass.

The above equation does not define the beam current density. This parameter is determined by the electrical field in the accelerator and work by Raimbault et al [5] has shown that the metal to metal breakdown voltage in the presence of a beam is essentially a linear function of the gap with an empirical constant given by:-

$$V/d_m = E_{max} = 6 \times 10^6$$
 [V/m]

where  $d_m$  is the metal to metal gap. The effective gap, d, is longer by a factor which depends on the geometry but is typically 1.4  $\pm$  0.2. Hence

$$V/d \le 4.3 \times 10^6$$
 [V/m] (6)

Substitution of Eq. (6) into Eq. (4) and division by the aperture area yields:

$$j \leq 6.3 \times 10^5 (V.A)^{-\gamma_2}$$
 [A.m<sup>-2</sup>] (7)

We can use Eq. (5) and the definition of the normalised rms emittance based on a thermal ion temperature,  $\rm T_i$  to derive the normalised beam brightness,  $\rm B_n$ , which is:

$$B_{n} = \frac{1}{\pi^{2} \epsilon_{nrms}^{2}}$$
where  $\epsilon_{nrms} = \frac{a}{2} \left(\frac{eT_{i}}{m_{i} c^{2}}\right)^{\frac{1}{2}}$ 

Hence after simplification of terms we have

$$B_n \leq 2.0 \times 10^6 \cdot (A/V)^{\frac{1}{2}} \cdot T_i^{-1}$$
 [A/ster/m<sup>2</sup>] (8)

Equations (5), (7) and (8) show that we can get a higher beam current but lower beam current density and brightness by increasing the beam energy. However, the maximum value of these terms are not functions of the accelerator geometry. In addition the extraction voltage is not usually a free parameter as it is usually determined by the accelerator function. In particle accelerators, for example, the following RF accelerator has a well defined input energy while in neutral beam injection for fusion the beam deposition in the plasma determines the beam energy.

### Multiple Apertures

Several methods have arisen to bypass the limitations described above. These are respectively the accel-decel accelerator column, the use of slit type extraction apertures and the multiple aperture accelerator. The former accelerator is similar to that shown in Fig. 1 except new the decelerating potential in the second gap is no longer negligible. The net result is to increase the extraction potential to a value significantly larger than the beam energy, hence raising the maximum current. However it can be shown that severe beam expansion occurs when the extraction voltage approaches twice the beam energy, so this method does not permit significant increases in beam current.

The second and third methods effectively increase the aperture area without increasing the value of a/d. An analysis of the optics of slit type apertures shows that a similar equation to Eq. (5) can be produced for slit beams except that I now represents current/unit length of slit. However both multiple apertures and a slit or multiple slits need a plasma which has a considerable spatial extent over which it is uniform in order to create a high current collimated beam. In view of this we limit the discussion to multiple circular apertures and the demands this places on the plasma generator.

The basic idea is extremely simple; a large number of apertures, N, all identical, are made so that the extracted current is

$$I_{N} \leq 5.36 \times 10^{-e} \text{ N V}^{3/2} / \sqrt{\Lambda} \qquad [A] \qquad (9)$$

We introduce here the concept of transparency, h, because there will always be annular zones round each aperture which cannot be used for extraction because of geometrical constraints or cooling. The transparency, h, is defined as:

$$h = N \pi a^2 / S \tag{10}$$

where S is the total area over which the apertures are distributed. As a result the average current density is lower by a factor of h than the extracted current density, and the beam brightness is also reduced by a factor of h as the transverse emittance increases by  $\sqrt{h}$  in both orthogonal directions.

The early high current accelerators relied on the thermal capacity of the electrodes and hence h was mainly determined by geometrical constraints. The theoretical upper bound for h in a hexagonal closepacked array is  $\pi/(2/3)$  or 0.90. However, the tapered shape to the beam forming aperture, the finite value of a and the need for mechanical stability, reduce h significantly. A typical example is the accelerator geometry for the DITE fusion experiment, where h is 0.6, a is 1.9 mm and N is 1724 [6].

The JET neutral beam injector is designed to produce a 60A, 80 keV of protons in a quasi-steady state [7]. As a result the beam power loading on the electrodes is approximately 100 kW per electrode (see next section), and considerable water cooling is required to remove this heat load. This causes a further reduction in h as the cooling channels interlace between the apertures.

Experimental evidence for the range of current densities over which the beams may be considered collimated have been given by Coupland et al [4]. This is approximately  $\pm$  5% of the current density corresponding to perveance match, although this rises to  $\pm$  10% for 4-electrode accelerators. As a result it is necessary for the plasma generator to produce a plasma which is uniform to these limits over the full area, S.

## Electrode Power Loading

In positive accelerator columns the extracted ions can interact with the background gas in the

extraction column and have charge exchanging collisions or ionising collisions. The former collisions simply produce a slow ion, which is then accelerated, and a fast neutral. These particles are not focussed and can have a significant probability of colliding with downstream electrodes. The ionisation collisions produce a slow ion and an electron which are accelerated in opposite directions. The electron beam can have a significant probability of striking the back of the plasma generator, which has to have additional cooling as this electron beam power can be similar to the total discharge power in large sources.

Several experiments have been made to examine the power loads on the accelerator structure , and these show that power loading is both a function of beam perveance and pressure. In the case of perveance, Raimbault et al [5] show that the minimum loading on the electrodes occurs slightly before the beam focus, and this may be caused by the increase in beam radius in the column with increasing values of k (or beam perveance), as shown in Eqs. (1) and (2).

The pressure scaling law of this accelerator heating has been examined by Holmes & Green [8] using a tetrode accelerator where a linear relationship has been observed. They have also measured the role of secondary electrons emitted from the negative electrode. These electrons are accelerated back towards the plasma source where they are indistinguishable from ionisation electrons. However, by varying the taper angle on this electrode (see Fig. 1) it is possible to show that a significant fraction of these backstreaming electrons can be eliminated, hence reducing the total back electron power loading.

#### Large Area Plasma Sources

The range of plasma source types for single aperture beams (or perhaps a few apertures) is very large as the zone over which the value of j has to be constant is small (typically 10 to 20 mm). However if we wish  ${\rm I}_{\rm N}$  to be in the multiple ampere range at high beam energies (~  $10^{\,\text{s}}$  eV) then j is low (~  $2000~\text{A/m}^2)$ and S is large (0.01 to 0.1  $m^2)_{\star}$ 

At present only two basic source types can meet this requirement, and they are the magnetic multipole type, first proposed by Limpaecher et al [9] but extended by Hemsworth et al [10] and Holmes et al [11]at Culham Laboratory, and the magnetic field free source developed by Ehlers et al [12] at Lawrence Berkeley Laboratory. Hybrid sources which are intermediate between these two forms have been developed by Stirling et al [13] and Bariand et al [14] which have some similarities to a duo pigatron.

In all these sources two objectives are essential: the current density must be uniform to within  $\pm$  5% over the entire area so that the beam from each aperture is collimated, and the value of S must be large enough to allow the required beam to be extracted. In addition there may be auxiliary requirements such as DC operation and a required ion species.

In the following section we will concentrate on just one plasma generator type, the magnetic multipole, as the experimental database is considerably larger than that for other types and it has the additional advantage of being a simple physical system.

#### The magnetic multipole source

An illustration of the magnetic multipole source is shown in Fig. 2. The basic source is a box or cylinder which is also the vacuum envelope and

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anode. This anode is covered by an array of bar magnets which form a high order multipole field which has the function of containing the discharge plasma and also fast ionising electrons which are emitted from the cathodic filaments. All ionisation and excitation collisions are made by these fast electrons, which gain their energy (equal to slightly more than the discharge potential) across the plasma sheath which covers the hot wire filaments (usually tungsten).

The sixth side of the chamber is the beam forming electrode of the accelerator, which can have one or many apertures in it according to the size of the source. This electrode is usually allowed to be at a floating potential relative to the discharge so that it collects equal fluxes of positive ions and electrons.

The main advantages of this type of source over its many competitors lies in its simplicity and flexibility. The magnetic multipole plasma confinement leads to a low ambipolar diffusion coefficient at the plasma edge in the high field region and a high diffusion coefficient over most of the interior volume where the field is very low. As a result the plasma density profile changes from a cosine type distribution which would occur if the diffusion coefficient is constant to one which is uniform but decreases rapidly at the edges in the high field region. A plot of the uniformity is shown in Fig. 3.

The same effect exists for the fast electrons, which hence provide a uniform ionisation rate to match the uniform plasma density. At the same time the fast electrons can be confined for a time sufficient for them to slow down completely in the plasma via inelastic collisions if the edge fields are sufficiently strong, hence raising the ion-electron pairs produced per fast electron to close to the maximum value permitted by the rate coefficient of ionisation relative to that of the total inelastic collisions.

Green et al [15] have created a model to derive the ionisation efficiency of a multipole source and also other source types which have ionisation via fast electron collisions. This model argues that the fast electron input per unit volume from the filaments is equal to loss via the sum of inelastic impacts and leakage to the walls with a time constant  $\tau_n$ , hence:

$$\frac{I_e}{ev} = n_p N S_{in} + \frac{n_p}{\tau_p}$$
(11)

where n  $_{\rm p}$  is the fast electron density, I  $_{\rm e}/{\rm eV}$  is the filament emission current per unit volume, N is the gas density and  ${\rm S}_{\rm in}$  is the inelastic collision rate. In the model the total ion production per unit volume  $I_+/eV$  is equal to the ionisation rate, hence:

$$\frac{1_{+}}{eV} = n_{p} N S_{i}$$
(12)

The ratio of these currents is hence:

$$\frac{I_{e}}{I_{+}} = \frac{S_{in}}{S_{i}} + \frac{1}{N S_{i} \tau_{n}}$$
(13)

The terms  $\mathbf{I}_{\mathrm{e}},~\mathbf{I}_{\mathrm{+}}$  to the beam forming electrode and N are readily measurable, hence allowing estimates of  $\tau_p$  and  $S_{in}/S_i$  to be made. An example of such a plot is shown in Fig. 4. Multipole sources using cobaltsamarium magnets can achieve confinement times of the order  $10^{-6}$  sec which allows the fast electrons to be fully used. As a result very high plasma production efficiencies can be achieved with values of  $I_{+}/I_{e}$  as large as 1.2 being possible (Holmes [16]). Even in very large discharge chambers, such as those designed for neutral beam heating on the JET tokamak or the JT50 tokamak [11,17],  $I_{+}/I_{e}$  as high as 0.4 has been achieved.

### Gas pressure in the discharge

The power loadings on the electrodes discussed earlier are proportional to the gas target in the accelerating column. This gas target is caused by the flow of gas molecules in the discharge chamber through the apertures in the beam forming electrode into the accelerator. Consequently, to avoid excessive beam power loads on the accelerating electrodes, the source operating pressure must be minimised while retaining the necessary ion current density and the plasma uniformity.

The minimum pressure for the discharge can be derived from Eq. (13). The maximum electron current that can be emitted from a hot filament is limited by the space charge of incoming ion flux from the plasma. In this limiting case the ratio of emission current density,  $j_{emax}$ , to ion current density is:

$$\frac{j_{emax}}{j_+} = \left(\frac{m_i}{m_e}\right)^{\frac{1}{2}}$$

However the emission current is related to the emission current density by the filament area,  $A_{\rm f}$ , and the positive ion current is equal to j<sub>+</sub> multiplied by the total ion collection area,  $A_{\rm i}$ , so that

$$\frac{A_{f} j_{emax}}{A_{i} j_{+}} = \frac{S_{in}}{S_{i}} + \frac{1}{N_{min} S_{i} \tau_{p}}$$

or

$$N_{\min} = [S_{i} \tau_{p} (\frac{A_{f}}{A_{i}} (\frac{m_{i}}{m_{e}})^{\frac{\gamma_{e}}{2}} - \frac{S_{in}}{S_{i}})]^{-1}$$
(14)

Equation (14) shows that the operating pressure is reduced by increasing  $\tau_p$  or  $A_f/A_i$ . Both of these are achievable by magnetic multipole confinement. The value of  $\tau_p$  approaches its maximum value set by inelastic friction in the plasma and  $A_i$  is reduced by the magnetic fields at the anode which restrict the ion loss area. However it should be noted that  $A_i$  cannot be smaller than the extraction area S, and is usually somewhat larger due to edge effects.

Eq. (14) also shows that the operating pressure is a strong function of the ion mass. The ionisation rate also increases with ion mass, leading to a minimum pressure which decreases approximately with the reciprocal of the mass.

## Modification of ion species

In many discharges the ion of a given element can have several states, for example in hydrogen H<sup>+</sup>, H<sup>+</sup><sub>2</sub> and H<sup>+</sup><sub>3</sub> ions are known to exist. This usually causes problems as frequently only one ion state is required and the others must be removed. In low current sources a simple bending magnet is usually sufficient at the price of increased complexity in the beam transport line. However in high current sources additional problems are created by the large beam power contained in the undesired ion mass fractions and by the large beam geometrical cross-section.

These problems can be reduced by modifying the source so that the plasma is formed primarily out of the required ion mass, hence resulting in a beam of the same mass. This has been achieved in hydrogen discharges by spatially modifying the electron energy distribution by the introduction of the concept of the magnetic "filter" [18,19]. This device is essentially

a sheet of magnetic field ( $\int Bdl \sim 2 \times 10^{-4}$  [T.m]) which divides the discharge volume into two regions: one where the ionisation of the gas occurs, which is kept separate from the extraction region, and the other where the electrons are much cooler and no ionisation occurs. As a result the molecular ions H<sup>+</sup><sub>2</sub> which are formed in the main ionisation event are broken up by impacts with cold electrons to form H<sup>+</sup>. As this process occurs near the extraction apertures the beam is formed primarily out of protons. So far this effect has only been exploited for hydrogen and deuterium discharges but it should be feasible for discharges in other molecular gases such as N<sub>2</sub>, O<sub>2</sub> or even the halogens.

The enhancement of fraction of the ion with the highest value of  $e/m_i$  is also increased by another effect which is associated with the magnetic filter. The filter impedes the flow of electrons towards the extraction plane [19] with the result that the plasma density and temperature of the electrons in the plasma production region both increase significantly. This has the result of increasing the proton fraction in this part of the plasma [20,21] and also increasing the atomic atom density which leads to direct H<sup>+</sup> production. The main reason for these effects lies in the fact that the  $H_2^+$  production rate is linearly proportional to the plasma density (or arc current) while the  $H^+$  production rate depends on collisions between  $H_2^+$  and electrons, hence having a quadratic dependence on the plasma density until the process saturates at high arc currents.

In the case of hydrogen and deuterium the main use of this effect has been in the development of neutral beam injection for fusion where the molecular ions  $\mathrm{H}_2^\star$  and  $\mathrm{H}_3^\star$  lead to the formation of lower energy neutral atom beams which give undesirable heating of edge of the plasma in the torus. The use of the magnetic filter here however has to satisfy the additional constraint of a uniform plasma so that the many beamlets which form the high current beam are all collimated for a single value of the discharge current. The simple dipole filter field used in the early work 18,19] is not sufficient and a new filter has been developed for the JET plasma source which has bilateral symmetry as shown in Fig. 5 [11]. This filter is created by the arrangement of the magnets on the outside of the source, as seen in Fig. 5. The filter field is emphasised by using linear cusps while the plasma confinement is obtained by the "checkerboard" magnet arrangement elsewhere which has a higher order of multipolarity. This gives a highly uniform plasma over the full useful plasma cross-section of  $45 \times 18$  $cm^2$  to within ± 5% while attaining an extracted proton fraction of 90% with a 60 A beam, as shown in Fig. 6. A similar source has been developed in Japan by Okumura et al [17], where an alternative filter geometry which is also symmetrical has been built.

The formation of a cold plasma near the extraction electrodes by the action of the magnetic filter has the additional advantage of enabling the creation of negative hydrogen or deuterium ions in the plasma to occur by dissociative attachment. This effect is now being exploited to extract high current beams of negative ions from plasma generators similar to that shown in Fig. 5 without the use of cesium.

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FIG. 1 Illustration of Triode Accelerator. The first Electrode is shaped to reduce beam aberrations while the second Electrode has a tapered profile to suppress secondary electrons from being accelerated towards the source. The third Electrode is at earth potential.



FIG. 3 The ion flux uniformity of a Multipole Source



FIG. 5 A Magnetic Multipole Source with a Symmetrical "Supercusp" Magnetic Filter

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FIG. 6 The Hydrogen Ion Species shown as a function of beam current for a Multipole Source with a Filter