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ION AND ELECTRON SOURCES

C.E. Hill

Abstract

Although the acceleration of particle beams is understood by accelerator physicists, the source of the primary particles if often cloaked in mystery. This paper will attempt to shed some light on the principles and operation of basic lepton and hadron sources commonly used in accelerators.

Talk given at the CERN Accelerator School "Cyclotrons, Linacs and their Applications", La Hulpe, Belgium, 28 April - 5 May 1994

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ION AND ELECTRON SOURCES

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Although the acceleration of particle beams is understood by accelerator physicists, the source of the primary particles is often cloaked in mystery. This paper will attempt to shed some light on the principles and operation of basic lepton and hadron sources commonly used in accelerators.

1 INTRODUCTION

During the design of a particle accelerator, the origin and identity of the particle is often treated as a mathematical fiction instead of an entity that must be produced at the beginning of the acceleration process. In many cases the source of the particles must be made to fit around the design instead of being taken into consideration at an early stage. However, accelerators are not the only users of particle beams. Applications range from providing beams of hundreds of Amperes for fusion applications, nano-Amperes for microprobe trace analysis, broad beams for ion implantation, space thrusters, industrial polymerisation, food sterilisation, to medical, military and accelerator applications. The types of particles involved are equally as numerous and are limited only by the availability of a suitable source. Table 2 shows a selection of ion source types which can be found.

Table 1
A selection of types of ion source

Surface ionisation
Field ionisation
Sputter
Laser
Electron beam ionisation
Arc discharge
Multipole confinement
Pennings
Charge exchange
Plasma beam
Duoplasmatron
Hollow cathode
Pigatrons
Multifilament
Cyclotron resonance
Surface plasma
Magnetrons
RF plasma

As can be seen, the field is vast and can not be covered in a paper like this. Instead we will cover some of those sources which are of interest to the accelerator field but it will reflect the bias of the author's experience. To someone interested in hadron sources, electron sources tend to be something of a mystery, but a simple introduction to electron devices will be given. This paper is intended to complement previous General Accelerator School presentations, especially those of N. Angert [1].

2 PLASMA AND POSITIVE IONS

2.1 Plasma and ionisation

In any gaseous discharge, both negatively and positively charged particles exist in approximately equal proportions along with un-ionized neutrals, i.e. they form a plasma. For a simple ion source, it is only necessary to extract the ion from the plasma and then to accelerate it. However, a reasonable current with good beam qualities is usually needed and the objective of source design is to optimise the desired ion yield and beam quality.

Electron bombardment ionisation of the neutrals in the plasma is the most general method of increasing the plasma density. Energetic electrons passing close to, or colliding with, an electron orbiting an atom can give energy to that electron. It then moves to a higher metastable orbit. However, if the orbiting electron gains sufficient energy it can leave the atom completely, leaving it ionised. This energy of the incident electron is known as the ionisation energy (or potential when expressed in eV). As more and more electrons are removed from the ion, more energy is required to remove the next electron due to the increased binding between the remaining electrons and the positive nucleus. Figure 1 shows the evolution of ionisation potential against charge state for the early atoms. The ionisation potential is only a threshold; ionisation efficiency increases with incident electron energy up to about three times the ionisation potential and falls off at higher energies.

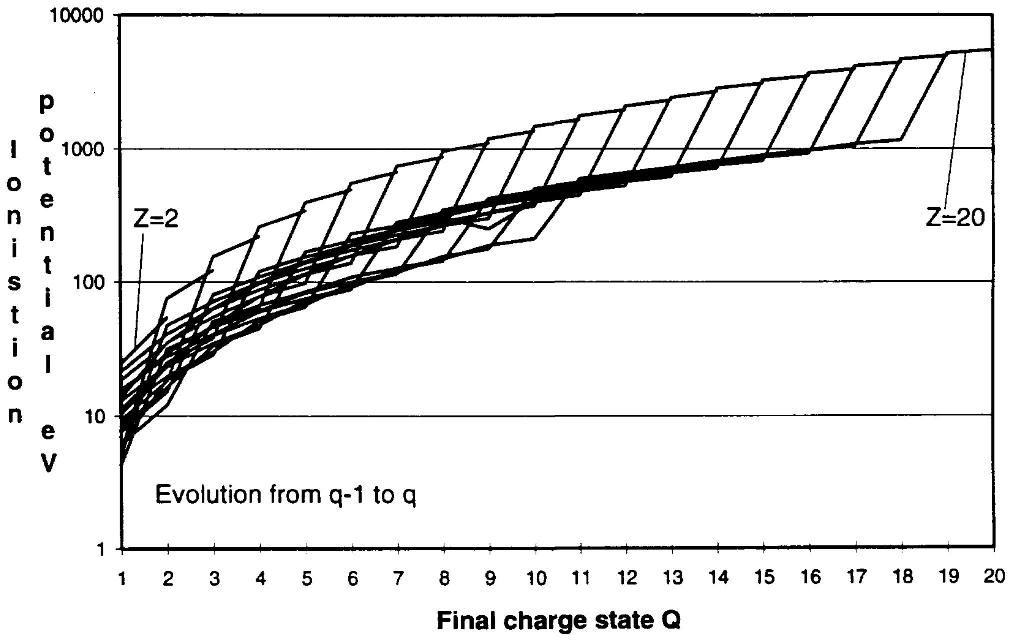

Fig. 1 Evolution of ionisation potentials for the lower atoms

2.2 Ionisation of hydrogen

From the above it may seem that electron bombardment ionisation is a simple process. However, in reality many processes are going on in competition in the plasma. The ion source must therefore enhance the production of the desired ion at the expense of other possible species. Even for a simple atom, like hydrogen, the processes in the plasma are believed to be the following:-

$$H_2 + \text{`ionisation'} \Rightarrow H_2^+ + e$$

$$H_2 + e \Rightarrow H_2^+ + e$$

$$H_2^+ + e \Rightarrow H^+ + H + e$$

$$H + e \Rightarrow H^+ + 2e$$

$$H_2^+ + H_2 \Rightarrow H_3^+ + H$$

$$H_3^+ + e \Rightarrow H^+ + H_2 + e$$

It is believed that the last two processes are important for the efficient production of protons.

2.3 Multiply-charged ions

Electron bombardment ionisation can result in the removal of more than one electron from an atom or ion provided the bombarding electron has sufficient energy. There are two routes by which this can occur. In SINGLE-step ionisation, the incident electron must have an energy of at least the sum of all the ionisation potentials of the removed electrons whereas in MULTI-step ionisation it requires only the energy of each electron removed. The processes are as follows:-

Single $A^{i+} + e \Rightarrow A^{(i+n)+} + (n+1)e$

Multi $A^{i+} + e \Rightarrow A^{(i+1)+} + 2e$

Table 2 shows some typical ionisation potentials for single and multi-step ionisation processes and it can be seen that single step requires considerably higher electron energies.

Table 2
Typical ionisation potential ranges

Ion	Ionisation Potential (eV)
Oxygen 5+ to 6+	138.1
Oxygen 0+ to 6+	433.1
Oxygen 7+ to 8+	871
Lead 26+ to 27+	874
Lead 0+ to 27+	9200
Lead 81+ to 82+	91400

The maximum charge state that can be attained is limited by the maximum incident electron energy.

Multi-step ionisation is thus the only really feasible route to high-charge-state ions but this process takes time. This time depends on the plasma density and the ionisation cross section and must be shorter than the ion lifetime in the plasma. The dependence of cross section on electron energy means that the high energies required to produce high-charge states are not an advantage for the production of low-charged seed ions. Ions are lost from the plasma by such processes as loss to the walls and electron capture from neutrals and plasma electrons. The design of high-charge-state sources is complicated by these phenomena.

3 POSITIVE ION SOURCES

3.1 The RF source

In the early days of CERN a radio frequency source of the Thonemann type shown in Fig. 2 was used [2]. An RF electric field coupled into the plasma chamber maintains a low pressure ($10^{-2} - 10^{-3}$ Torr) discharge. Positive ions are expelled from the discharge by a negatively biased repeller electrode. Plasma density is somewhat limited by self shielding of the plasma and losses to the walls. Shielding effects could be alleviated by increasing the RF frequency. The application of a magnetic field to the plasma bottle increases ion production by lengthening the path of ionising electrons and reducing their drift to the walls. However, metalisation of the plasma bottle during operation can give rise to reliability problems.

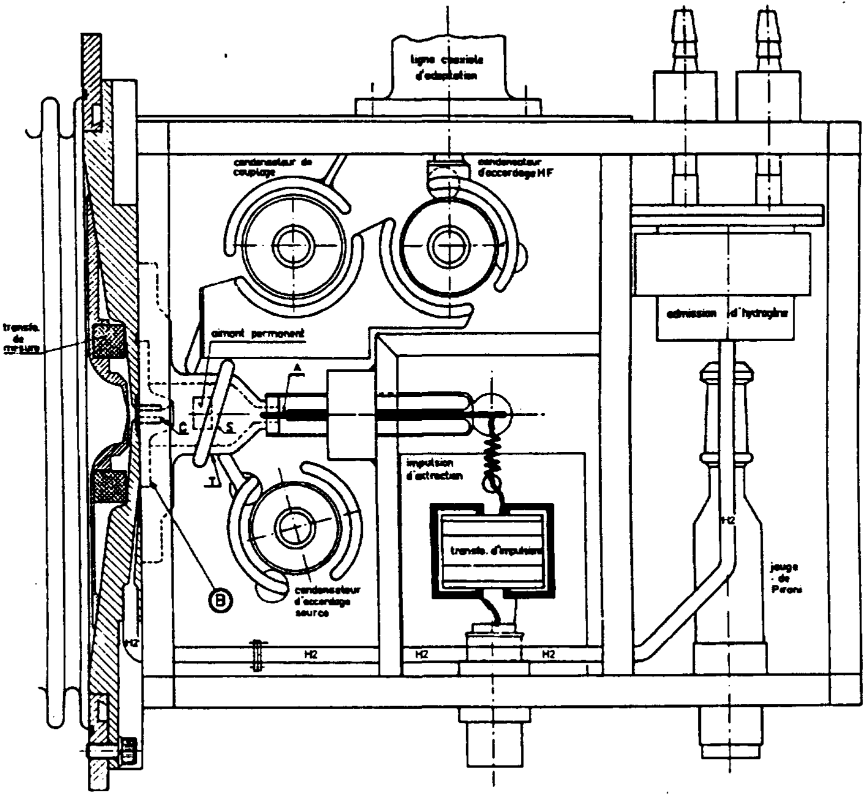

Fig.2 CERN RF ion source

3.2 Penning type sources

At 10^{-1} Torr and 1kV it is possible to strike an arc with almost any electrode configuration but the discharge will be too unstable for practical use. If a ring or cylindrical anode is immersed in an axial magnetic field with an electron emitter perpendicular to that field, electrons in the discharge plasma are forced into cycloidal paths thus increasing their path to the walls and increasing, thereby, the probability of an ionising collision with the neutrals. The working pressure and ignition voltage can be reduced to more reasonable values. This discharge, the Penning discharge, is used in a number of sources with either cold (cf. Penning vacuum gauge [3]) or hot thermionic emitter and can be used for low-charge-state light ions. These sources have an advantage in cyclotrons in that they can use the machine's own magnetic field. A typical hot cathode Penning (PIG or Reflex) source is shown schematically in Fig. 3.

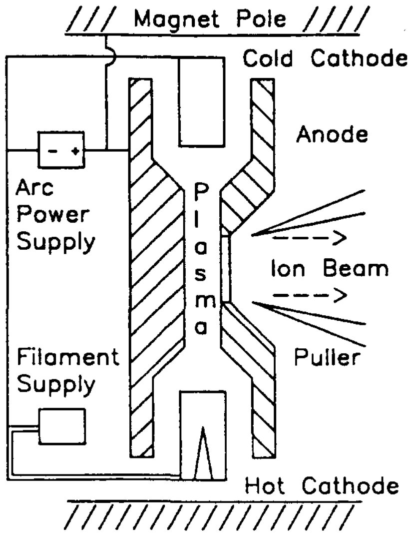

Fig. 3 Schematic hot cathode Penning

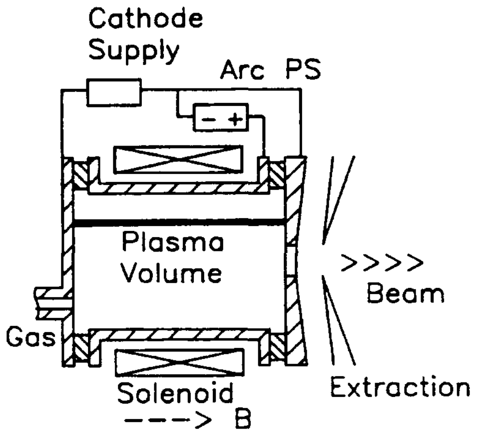

Fig. 4 Axial extraction Magnetron

If the electron emitter is placed parallel to the magnetic field, the source becomes a Magnetron (Fig. 4).

3.3 Plasmatrons

The current extracted from an ion source is dependent on the density of the plasma in the extraction region. Constricting the discharge, for example near the anode, not only increases the plasma density but also increases potential difference across the restriction which increases the energy of the primary ionising electrons (Unoplasmatron). Further compression and consequent further heating of the electrons can be achieved by adding a strong magnetic field around the constriction, and by controlling the primary plasma and magnetic compression it is possible to optimise the yield of the desired ion. Figure 5 shows an idealised potential distribution in the constriction. The anode plasma is allowed to escape through a small aperture in the anode and it is from this plasma that ions are extracted. Normally, the plasma streaming through the anode hole would be too dense to allow the extraction of ion beams with good optical properties so the plasma is allowed to expand into some form of expansion cup. This principle is used in the Duoplasmatron source.

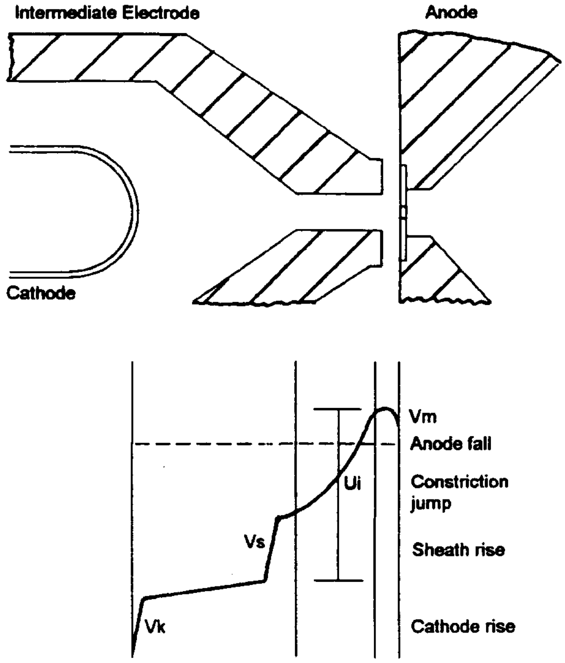

Fig. 5 Idealised potential distribution in the duoplasmatron discharge

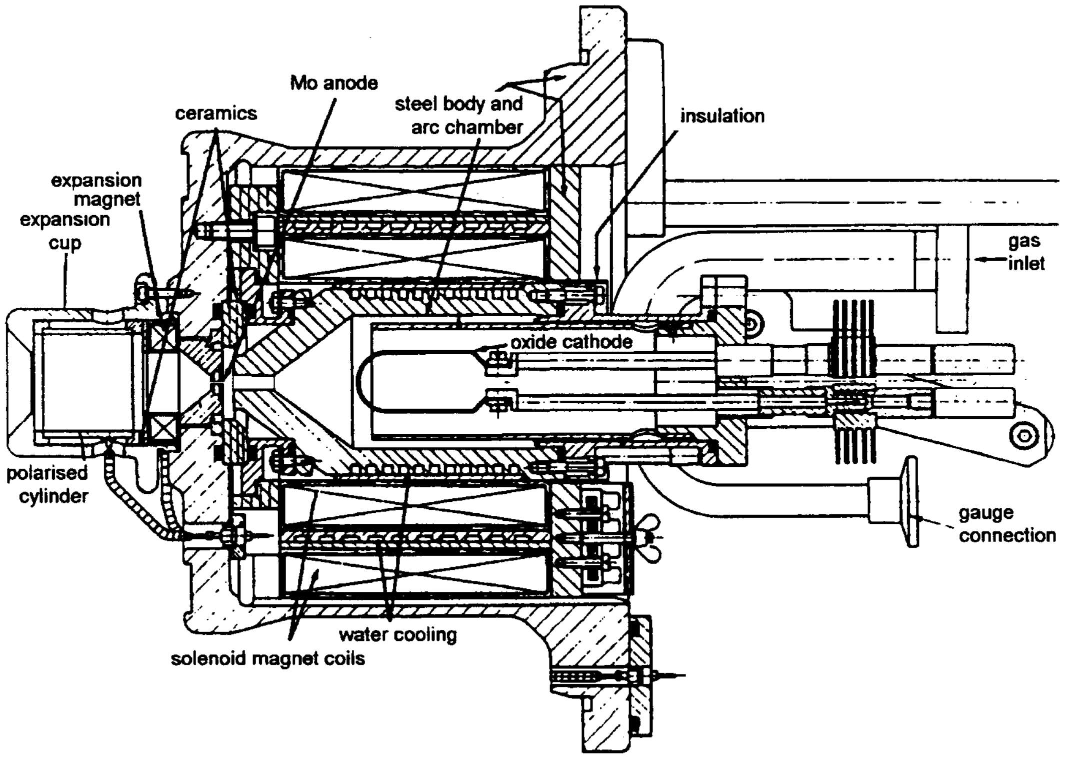

Fig. 6 CERN standard duoplasmatron (with polarised expansion cup)

The CERN pulsed duoplasmatron [4,5], shown in Fig. 6 has a water cooled shaped iron plasma chamber with the constriction towards the anode. A solenoid surrounding the plasma chamber provides the field for magnetic compression in the constriction canal. The expansion cup is rather deep and contains an additional small solenoid to fine trim the plasma characteristics. Additionally, the cup contains a negatively biased electrode which can increase beam output probably by repelling electrons back into the streaming plasma and causing secondary ionisation near the anode.

This source is routinely used to produce protons with beam pulse intensities of up to 500mA but has also been used to produce deuterons and alphas. The low energy and poor confinement of the primary ionising electrons in the anode plasma limits the performance to anything other than singly-charged ions.

3.4 Multipole confinement sources

The density of a plasma is dictated by the balance between production and loss processes, with the added restriction that to maintain neutrality the ion charge and electron charge densities must be equal. Energetic electrons, which are more useful for ionisation, are more easily lost to the chamber walls than the slower ions unless steps are taken to return the fast electrons to the plasma. It would also be of advantage to allow slow electrons with less than the minimum ionisation energy to escape thus reducing the possibility of electron-ion recombination. A strong multipole magnetic field surrounding the plasma volume meets these requirements. As with PIG sources, the increased path length of the energetic electrons increases the probability of ionisation, whilst cold electrons spiralling down the field lines have more chance to be lost on the walls. Improvements in ion ionisation efficiency result in a reduction of neutral pressure for the same plasma density which can make for a more open source and ease vacuum pumping requirements.

Sources based on permanent magnet multipole confinement have been developed since about 1975 [6,7] with uses in fusion research as the main driving force. Figure 7 shows a pulsed multipole developed for accelerator use [8] and Fig. 8 shows a typical multipole field configuration. The main advantages of these sources is their low operating pressure, a stable plasma and that they can be made to almost any size provided there are not too many holes in the multipole field configuration.

3.5 Electron cyclotron resonance (ECR)

Energetic electrons rotate in a magnetic field, B, with a frequency defined by the relation $\omega = e.B/m$ or in engineering units 2.8GHz/kG. In a box immersed in an arbitrary magnetic field there can exist a surface where the above relationship holds. If the radio frequency power of this frequency is injected into the box, plasma electrons crossing this surface will, in general, be heated and can be used for ionisation of the plasma. The plasma density can therefore increase up to a value which is believed to be limited when the plasma frequency, which is a function of the density, exceeds the RF frequency. With adequate confinement of the plasma and the use of microwave frequencies, high electron temperatures can be attained making this principle interesting for multi-charged ion production.

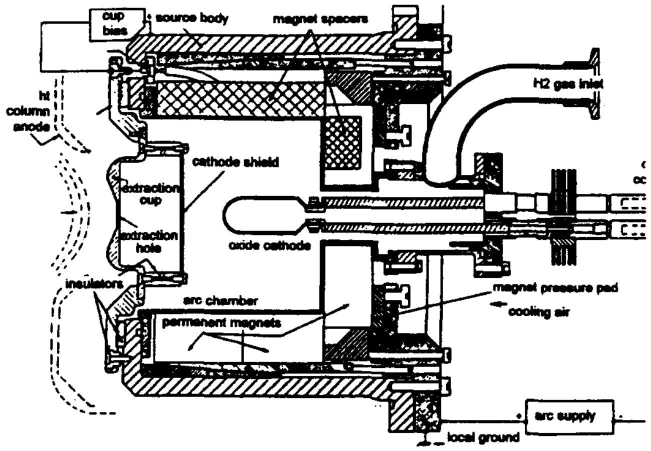

Fig. 7 Experimental multicusp source for protons

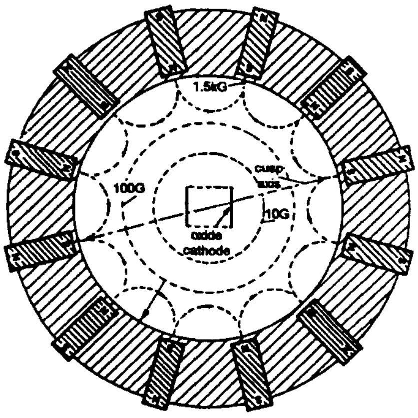

Fig. 8 Magnetic field inside plasma chamber

The ECR ion source (ECRIS or ECR) [9] makes use of this effect using microwave frequencies. Longitudinal confinement is achieved by Helmholtz coils configured to give a 'minimum B' field configuration and radial confinement by powerful permanent magnet multipoles. Figure 10 shows the typical longitudinal field set up by the coils. Plasma densities greater than 10^{12} cm^{-3} can be attained. This type of source is used routinely on heavy-ion cyclotrons and has been used in the pulsed mode on synchrotrons for the production of O6+ and S12+ beams.

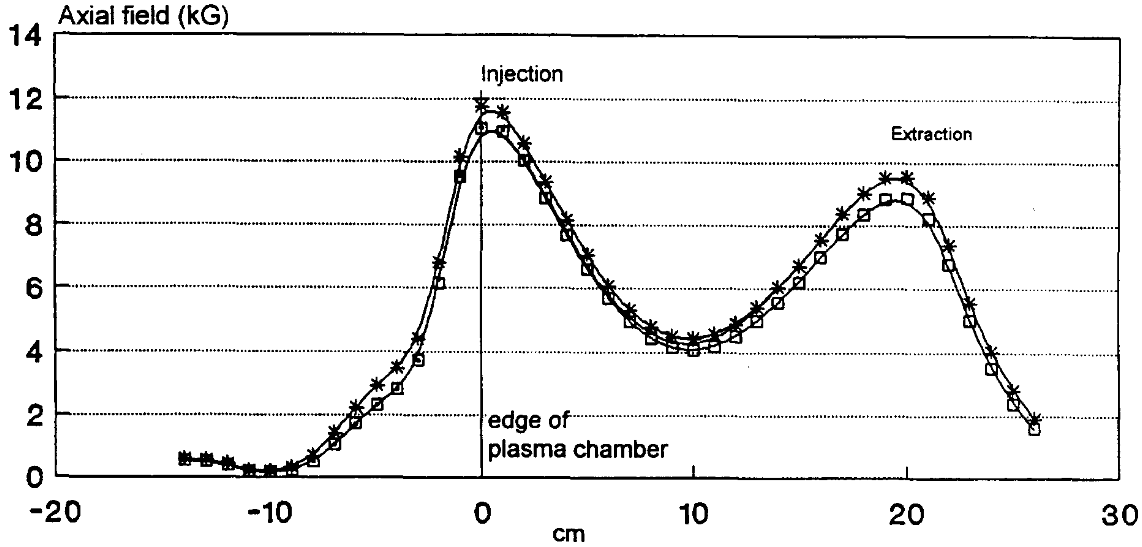

Fig. 9 Typical longitudinal field in an ECR source

In the ECR plasma, there is one phenomena that in recent years has made higher currents of highly-charged ions available. Normally an ECRIS gives a better performance when used in the pulsed mode as compared to dc operation. However, it is possible to adjust a pulsed source in such a way that when the RF heating power is turned off, a large peak of highly charged ions appears. This effect, known as 'Afterglow' is believed to be due to a rapid loss of plasma electrons and the deconfinement of positive ions [10].

Afterglow is used in a CAPRICE type ECR developed at GANIL for use at CERN [11]. This source is a steel bodied source with minimum B coils and a permanent magnet hexapole. Figure 10 is a schematic of this source. In normal operation it has given pulsed beam currents of 80μA of Pb 27+ suitable for synchrotron use.

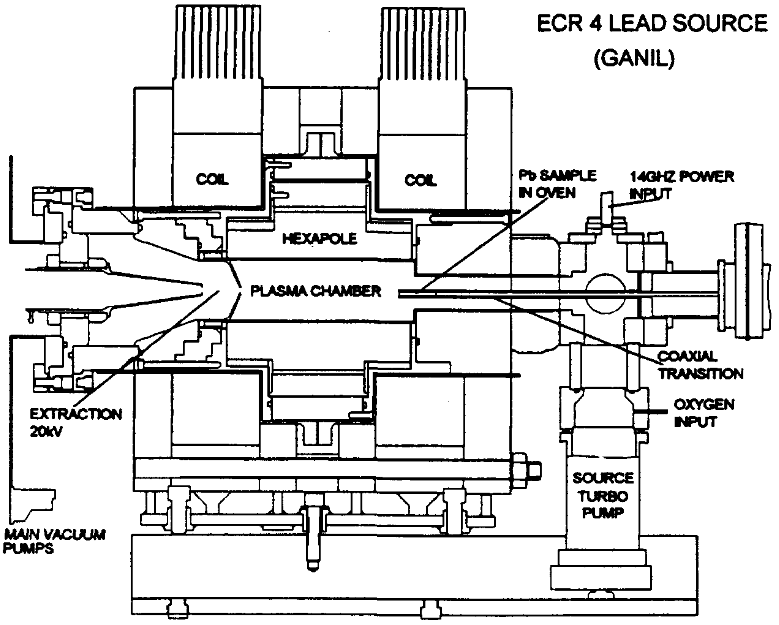

Fig. 10 An ECR source for lead ions

3.6 Electron beam ion source

In the Electron Beam Ion Source (EBIS), a fast, dense, electron beam interacts with cold ions trapped in an electrostatic well. Ions are confined radially by the potential well in the electron beam and axially by electrostatic mirrors. Ions accumulated in the trap can be expelled by lowering the potential of one end of the trap. As the interaction time between hot electrons and ions depends on the electron energy and the source length, for highly charged ions this time is necessarily short. Thus high density, and hence high current density, electron beams are required. In practice of the order of 1000A/cm^2 is needed. As normal thermionic cathodes are usually limited to less than 100A/cm^2 some form of beam compression is needed, and to maintain this beam against space charge forces the source is normally immersed in a solenoidal magnetic field. Correct configuration of the solenoid field will also give the compression. [12,13]

A schematic of an EBIS with ionisation of the sample gas in the trap is shown in Fig.11. Apart from this mode of operation, ions from a traditional source can be injected into the trap and further ionised by the electron beam. In view of the trap nature of the source, the ionisation process can be allowed to continue for a relatively long time making this source interesting for high charge ions for slow cycling accelerators. Care is needed with the very high current densities involved -- in most cases the electron beam is blown up in the collector (anode) and the energy in the beam recovered if this is felt to be worthwhile.

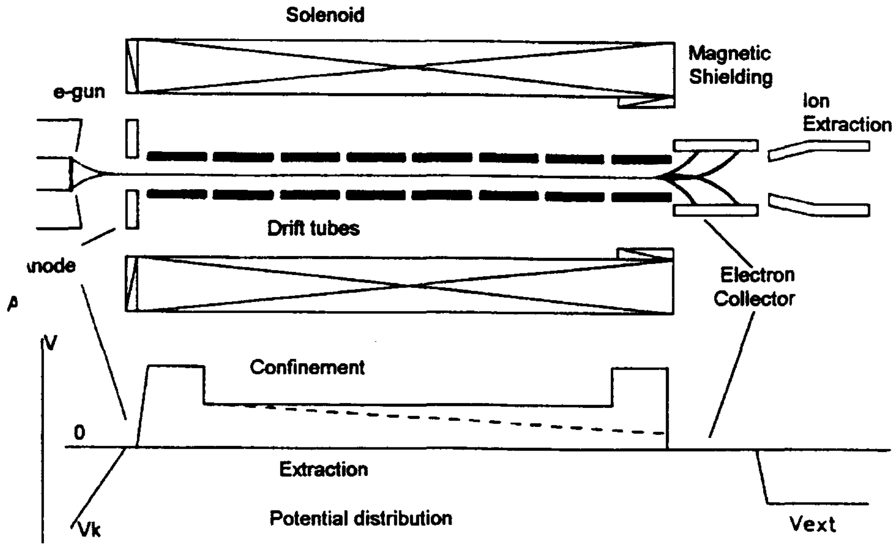

Fig. 11 Schematic confined flow electron beam ion source (EBIS)

4 NEGATIVE IONS

4.1 Introduction

Whereas the ions discussed up to now had a net positive charge, ions with a net negative charge (i.e. more electrons than protons) have gained popularity in the accelerator field. They were originally used to double the effective energy of electrostatic machines by stripping the excess electron, and the natural one at the high potential electrode, and re-accelerating the resultant positive ion. Although often used in accelerators for charge exchange injection from linear to circular machines [14], negative ions are also used for fusion plasma heating, directed energy weapon research and semiconductor processing.

The physical processes in negative ion sources are still poorly understood but three types of source are generally recognized; surface, volume and charge exchange. These processes, although dominant in one type of source, may also be present to some extent in all negative ion sources and will be discussed under each type. It should not be forgotten that electrons and negative ions have the same charge and thus both will be extracted from the source -- the electrons in large quantities. Elimination of this unwanted electron component is one of the major technological problems in negative ion source design.

4.2 Surface formation

Historically, negative hydrogen ion sources were modifications of existing proton sources such as duoplasmatrons with the ions extracted from the anode plasma off axis. Insertion of a floating electrode into the channel of the plasma chamber improved the yield of negative ions but the addition of caesium to the discharge dramatically increased the ion current (and electrons) [15].

The increase in source efficiency from the addition of caesium accelerated the development of higher intensity devices based on the cold cathode magnetron geometry. It transpired that it was more important to have a negatively biased caeseated (or low work function) surface in the discharge plasma than to have caesium in the discharge. Various miniature geometries have been developed using the cathode as the support for the caesium (Penning, magnetrons, planotrons) [16,17].

There is still no clear evidence as to what is happening inside a caeseated discharge. All or some of the following processes may be involved:-

1) Dissociation of plasma produced caesium hydride

$$Cs + H \Rightarrow CsH \Rightarrow Cs^{+} + H^{-}$$

2) Sputtering of lightly bound ions from the surface
3) Attachment of an electron after scattering from the surface

However, it is known that the surface coverage is important (about 0.7 monolayer) and that the energy of the incident ion must be low (> a few hundred eV). The importance of the coverage is such that as the duty cycle and the discharge power increases it becomes more and more difficult to maintain it. However, these sources can work in the steady state mode and Fig.12 shows such a source. The magnetic field of the source can be used to eliminate the electrons before acceleration.

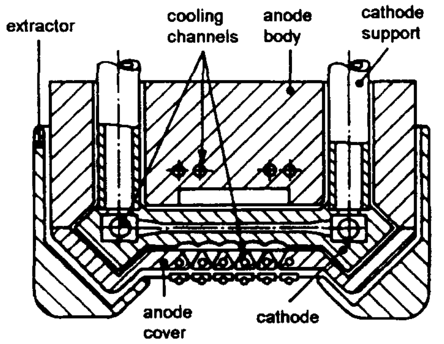

Fig. 12 Cross section of a steady state magnetron negative ion source

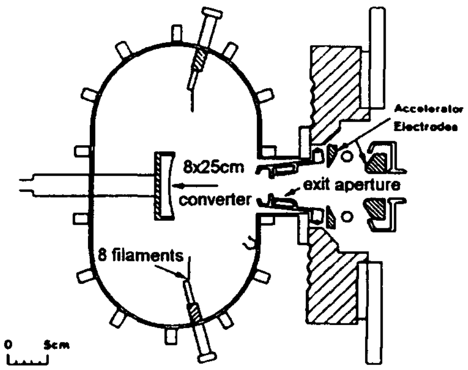

Fig. 13 LBL surface production multipole negative ion source

Unfortunately, these sources have a poor gas efficiency requiring large quantities of gas and hence large pumping systems or pulsed gas supplies. Some of these problems can be reduced if the plasma generation can be made independent of the conversion process. Fitting a negatively biased curved converter plate, with its centre of curvature in the extraction aperture, into a standard proton multipole confinement source gave extractable negative ion currents whose intensity could be enhanced by caesium [18,7]. This gave all the advantages of the multipole source. Careful arrangement of the electric and magnetic fields around the extraction aperture reduces the electron current to acceptable levels. A source incorporating these features in shown in Fig.13.

4.3 Volume production

Measurements of the negative ions in large-volume, low-pressure hydrogen discharges indicated densities which were much larger than those predicted by theory [19]. Theoretical and experimental studies showed that dissociative attachment of electrons to highly excited molecules was enhanced relative to attachment to ground state molecules. The addition of a small dipole magnetic filter in the plasma volume of a standard multipole source, thus separating it into two regions, enhanced the H^- yield due to this process [20] whilst reducing the electron component. It is believed that the ion formation is a two stage process:-

1) In the production volume between cathode and filter, hot electrons (100 - 200eV) ionise and vibrationally excite hydrogen molecules,

$$H_2 \quad + \quad e \; > \; {}^*H_2^+ \quad + \quad 2e \; > \; {}^*H_2 \quad + \quad e$$

2) Excited molecules and cold electrons (few eV) only diffuse past the filter. Dissociative attachment between molecules and electrons takes place in this volume,

$$^*H_2 \quad + \quad e \; > \; {}^*H_2^- \; > \; H^- \quad + \quad {}^*H$$

Hot electrons that pass the filter would quickly strip the negative ion as the extra electron is only loosely bound (0.7eV).

Careful choice of the bias of the electrode which closes the front of the plasma volume and of the source operating pressure can reduce the electron component to very low values. The good gas efficiency of the multipole and the absence of caesium make this source interesting for both fusion and accelerator use. A prototype source for an accelerator application [21] is shown in Fig. 14. Again, the addition of caesium to the discharge has recently been shown to enhance the yield [7].

4.4 Charge exchange

Double charge exchange of positive (or neutral) ion beams on alkali metal vapour targets was once a favoured method of negative ion production,

$X+ \quad + \quad Cs > X \quad + \quad Cs+$ (neutralisation)

$X \quad + \quad Cs > X- \quad + \quad Cs+$ (ionisation)

Although this method is falling out of use for high currents because the reaction cross section falls rapidly with incident particle energy above a few keV, this technique is used for exotic ion production such as polarised negative ions [22].

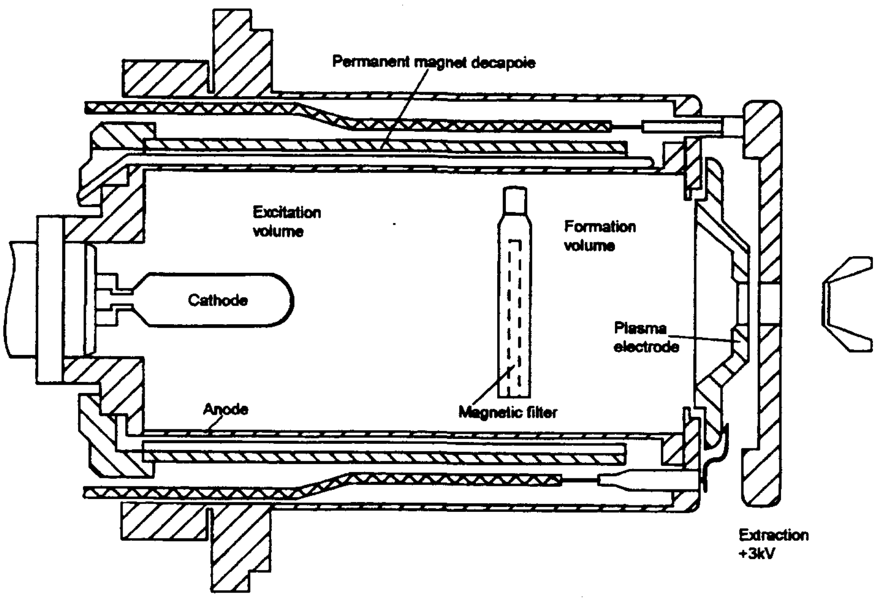

Fig. 14 Prototype volume production, multipole, negative-hydrogen-ion source

5 ELECTRON SOURCES

5.1 Introduction

In any plasma, electrons exist in abundance and in the case of negative ion sources are even a problem. Many ion sources use a source of electrons in their design to give an initial supply of ionising electrons or use a high quality electron beam. Plasma generated electrons can be used as sources of electrons but in many cases the quality and stability of the beam can leave a lot to be desired. To obtain good characteristics, the electrons, in general, need to be emitted from a well defined surface in a controlled manner. The actual design of an electron gun is mainly a function of the use of the required beam and in general is amenable to computer simulation. Only the basics of electron emission will be dealt with here; the formation of the beam is dealt with in specialist texts (e.g. [23]).

5.2 Thermionic emission

Thermionic emission is the escape of electrons from a heated surface. Electrons are effectively evaporated from the material. To escape from the metal, electrons must have a component of velocity at right angles to the surface and their corresponding kinetic energy must be at least equal to the work done in passing through the surface [24]. This minimum energy is known as the 'work function'. If the heated surface forms a cathode, then at a given temperature T (° K) the maximum current density emitted is given by the Richardson/Dushman equation:-

$$J = A \,.\, T^2 \,.\, e^{(-11600 \,.\, \phi \,/\, T)}$$

where ϕ is the work function (eV) and A is a constant with a theoretical value of 120 A/cm^2.K. In reality this value is not attained for real materials. Table 3 illustrates the basic characteristics of some thermionic emitter materials that are commonly used. It can be seen that the most important parameter for thermionic emission is that the work function as should be as low as possible to use a cathode at an acceptable temperature. The mixed oxide cathode is commonly found in small radio type valves. Cs/W/O, although not good for thermal emitters, is usually found in photo-tubes whilst the heavy metal cathodes are used in high power electron tube devices.

Table 3

Important characteristics of some thermionic emitter materials

Material	A	ϕ	Temp (° K)	J (A/cm^2)
Tungsten	60	4.54	2500	0.3
Thoriated W	3	2.63	1900	1.16
Mixed oxides	0.01	1.	1200	1.
Caesium	162	1.81		
Tantalum	60	3.38	2500	2.38
Cs/O/W	0.003	0.72	1000	0.35

In a diode structure, electrons leaving the cathode surface lower the electric field at the surface. A stable condition exists when the field is zero as any further reduction would repel electrons back to the cathode. This stable regime is known as 'space-charge-limited emission' and is governed by the Child Langmuir equation:-

$$J = P . V^{3/2}$$

where P, a constant which is a function of the geometry of the system, is known as the perveance. However, if the voltage becomes sufficiently high, the Richardson limit for current is reached when the emission becomes temperature limited. Figure 15 shows the characteristics of an ideal diode.

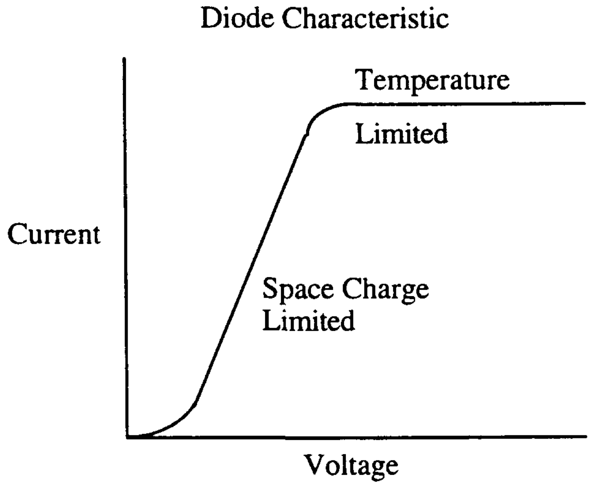

Fig. 15 Thermionic emission regimes

Thermionic emitters are used in electron tubes and in specialist electron guns, as for example in klystrons, welding, industrial materials processing and in accelerators for lepton production. Figure 16 shows a computer simulation of an electron gun used for hadron beam cooling.

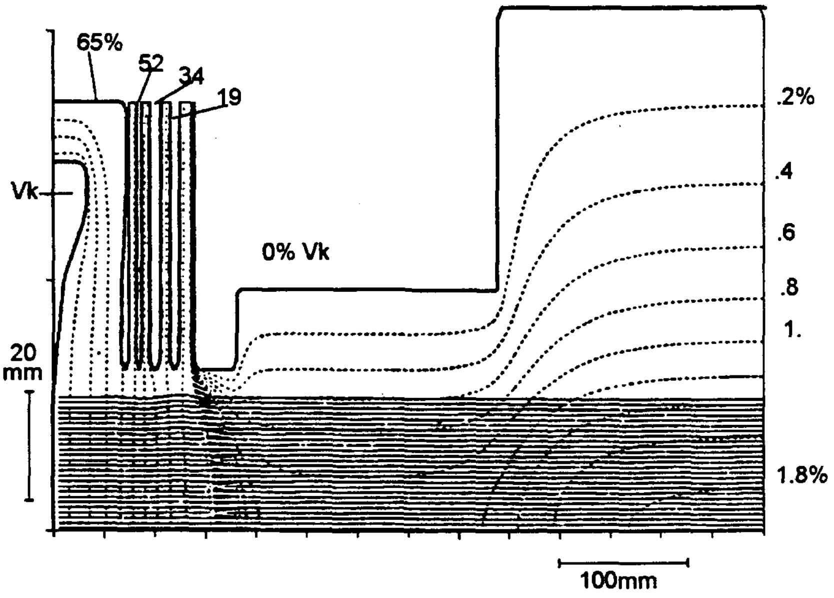

Fig. 16 Computer simulation of an electron gun

5.3 High field emission

The application of a high voltage between a fine point cathode and a contra surface can, by a tunnelling effect, give sufficient energy to an electron so that it escapes from the surface. This phenomena is known as high-field or Fowler/Nordheim emission. It should not be forgotten that the electric field around a point is greatly enhanced relative to the apparent average electric field between the electrodes. The current density (A/m^2) emitted by such a point is given by :-

$$J = (1.54 \,.\, 10^{-10} \,.\, E^2 / \phi) \,.\, e^{(-6.83 * 10^9 \,.\, \phi^{3/2} \,.\, k / E)}$$

Where E is the electric field at the emitter, ϕ the work function and k a constant approximately equal to 1.

With fields of the order of 10^9V/m, current densities can attain 10^{12} A/m^2 but the actual current is quite small due to the small surface of the emitter. More reasonable currents can be obtained by multiplying the emitter sites. Needles or razor blades can be used as emitter arrays and arrays etched in silicon have shown some success in electron tubes. The major disadvantage of this type of source is that an excessive current density can destroy the points either by erosion or self heating.

5.4 Photo emission

Photons illuminating a metal surface may also liberate electrons. If the photon has an energy at least equal to the work function, then electrons will be emitted, i.e.:-

$$\lambda < h \,.\, c \,/\, e \,.\, \phi$$

where λ is the wavelength of the incident light, c the velocity of light and h Plank's constant. For shorter wavelengths the electrons are emitted with an initial velocity given by

$$1/2 \,.\, m \,.\, v^2 = h \,.\, \nu \; - e \,.\, \phi$$

but in general these velocities are low. To obtain reasonable emission with normal wavelengths, a low work function material is needed, for this reason the Cs/O/W material mentioned earlier is often used in photo tubes. Intense electron beams require intense light sources, and lasers have been used to obtain very short high intensity electron beam pulse trains intended for the generation of microwave power in future linear colliders.

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