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PARTICLE PRODUCTION
FOR ACCELERATORS

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ABSTRACT

Although the production and use of secondary 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 operation of these sources.

1. INTRODUCTION

In discussions on particle accelerators, the identity of the particle being accelerated is often treated as a mathematical fiction instead of a real physical object that must be produced at the begining of the acceleration process. Essentially there must be a SOURCE of ionised particles, and Table 1 lists a small selection of the multitude of particle beams that can be produced for various scientific and industrial purposes..

Table 1. A selection of particle beams

Atomic beams
Positive ion
Molecular ion
Multi-charged ions
Heavy ions
Anti ions
Neutral beams
Negative ion
Singly charged ions
Polarised ions
Cluster ion
Electron

As well as the diversity of the beams that can be produced there is an equally large diversity in the types of ion sources available. Table 2 lists a selection of ion sources that can be found. When designing a particle beam system, the ion source is often the last item to be considered. Table 3 shows the wide range of ion source requirements.

Table 2. A selection of types of ion source

Thermal surface ionisation
Field ionisation
Spark ionisation
Sputter
Laser source
Electron beam ionisation
RF plasma
Hot & cold cathode Pennings
Hot & cold cathode Magnetrons
Primary electron collision
Arc Discharge
Plasma Beam
Unoplasmatron
Duoplasmatron
Hollow cathode
Duopigatron
Multifilament
Multicusp confinement
Surface plasma conversion
Volume multicusp
Cyclotron resonance
Charge exchange

Table 3. Range of ion source Technology

MICROPROBE ANALYSIS 0.1-1μA, P,D,Alpha, 0.5-5MeV diameter 1-5μm ---------------- MULTICHARGED ION BEAMS O^{6+} 80-100μA 130keV/n ---------------- LINAC 2 CERN P 350mA 760keV 10^{-4} duty D 20 mA 403 keV	FUSION EXPERIMENTS MFTF D 2x4.2A, 200keV, 100hour MARS D 8.9MW INJ, 5.7MW eff FedA D 100A, 400keV, 12% duty +60A, 800keV, CW FedR D 200A, 250keV, CW T 200A, 250keV, CW ------------------- Star Wars ?

With this enormous range of types and powers it is impossible to study all of them. Thus this paper will try to present some of the more interesting primary particle ion sources on modern accelerators. Electron and anti-ion sources will not be treated. This paper is intended to be complimentary to that of N. Angert[1] presented at the first CERN Accelerator School general accelerator physics course.

2. PLASMA SOURCES FOR POSITIVE IONS

In any form of gaseous electrical discharge, both negatively and positively charged particles exist in approximately equal quantities along with un-ionised species, i.e., they form a plasma. For a simple ion source, it is only necessary to extract the ion and accelerate it. However, higher currents are usually required and the main problem in ion source design is to optimise the production of the desired species. In plasma sources this is generally done by electron bombardment.

In the case of hydrogen, the processes to produce the singly-charged ion, the proton, are as follows:

$$
\begin{array}{lll}
H_2 + \text{ionisation} & \rightarrow & H_2^+ + e \\
H_2 + e & \rightarrow & H_2^+ + 2e \\
H_2^+ + e & \rightarrow & H^+ + H + e \\
H + e & \rightarrow & H^+ + 2e \\
H_2^+ + H_2 & \rightarrow & H_3^+ + H \\
H_3^+ + e & \rightarrow & H^+ + H_2 + e
\end{array}
$$

It is generally believed that the last two processes are important in the efficient production of protons. For higher charge states, a step by step ionisation process can take place:

$$X^{n+} + e \rightarrow X^{(n+1)+} + 2e$$

2.1 RF source

In the early days of CERN a radio frequency ion source of the Thonemann type, as shown in Fig. 1, was used[2]. Here 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 the negatively biased electrode A. The density of the plasma is somewhat limited by self-shielding of the plasma and by loss of plasma to the walls. Shielding effects could be overcome by increasing the RF frequency. The application of a magnetic field to the plasma bottle increases the production of ions by increasing the path length of ionising electrons and by reducing their drift to the walls. Metallisation of the plasma bottle during operation, however, can be a problem.

2.2 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 much too unstable for practical use. However, if a ring or cylindrical anode is immersed in an axial magnetic field with an electron emitter (cathode) perpendicular to that field, electrons emitted in the discharge are forced into cycloidal paths thereby increasing their path lengths, and thus the probability of ionisation. By this astuce the working pressure and the ignition voltage can be reduced. This, the Penning discharge, is used in a number of sources with either cold (cf Penning vacuum gauge)[3] or hot thermionic emitters. A typical hot cathode Penning (PIG or Reflex) source is shown in Fig. 2.

If the electron emitter is placed parallel to the magnetic field, the source becomes a Magnetron source (Fig. 3).

2.3 Plasmatrons

The current extracted from an ion source depends on the plasma density in the extraction region; thus, to improve source efficiency, some means has to be found to compress the density of primary ionising electrons there. Placing a constriction in the discharge, for example near the anode, increases the electron density in that region. The double layers so formed locally increase the electric field which heats the electrons. These newly excited electrons further contribute to the ionisation process (Unoplasmatron).

Adding a strong magnetic lens to the constriction further increases the local electron density by compressing the discharge into an even smaller channel. This combination of electrostatic and magnetic focusing not only increases the local plasma density, but also increases the energy of the primary ionising electrons. The ion source using this compression technique is known as the Duoplasmatron. Ions from the plasma stream through a small aperture in the anode but their density is still too high for good beam optics. Therefore, the plasma jet is allowed to expand into a plasma cup where the density falls to an acceptable value. The ion beam is extracted from this plasma.

Figure 4 shows an idealised potential distribution in the Duoplasmatron. The potential difference Ui between the inlet and outlet of the constriction or channel is that which basically defines the energy of the primary ionising electrons, and hence the effectiveness of the ionisation process. Around the cathode a double layer is formed from two counterstreaming currents of electrons and ions. This sheath is only stable if the ratio of these currents exceeds a value given by:

$$\frac{j^{+}}{j^{-}} = \sqrt{\frac{m}{M}}$$

otherwise oscillations will occur. From this relationship it can be seen that an isotope effect exists, the stable ion current decreases with atomic mass for a given arc (electron) current in the source.

The CERN Duoplasmatron [4,5], shown in Fig. 5, has a shaped iron constriction surrounded by a solenoid. An additional ring magnet in the expansion cup is used to shape the plasma density and distribution for optimal ion extraction. Although this source can operate as other duoplasmatrons with shallow expansion cups, a deep cup with a negatively biased electrode is used in practice. This electrode is believed to increase the proton yield by repelling and heating electrons in the cup, thus causing further ionisation of neutral and molecular ions.

As a source of protons with an arc voltage and current of 80V and 40A, up to 400mA (125mA/cm) can be extracted from the CERN source. For deuterons under similar arc conditions the current falls to around 150mA. Production of α-particles proved to be more difficult due to the low primary electron energy, but reasonable quantities of He^{+} could be produced.

2.4 Multipole confinement

The density of a plasma is dictated by the balance between production and loss processes, with the additional restriction that to maintain neutrality the ion and electron densities must be equal. Energetic electrons, which are more useful for ionisation, are more quickly lost to the chamber walls than the slower ions unless steps are taken to return these fast electrons to the plasma volume. It would also be of advantage to allow slow electrons with less than the minimum ionisation energy to escape, thereby reducing the chances of electron-ion recombination. Surrounding the plasma volume with a strong multipole magnetic field meets these requirements. As with PIG sources, the increased path lengths of the energetic electrons increases the chance of an ionising collision with the ions, whilst the spent electrons can spiral down the field lines to be lost on the chamber walls. Improvement in ion ionisation efficiency will result in a further reduction of pressure in the discharge chamber for a given plasma density.

Sources based on permanent magnet multipole confinement have been developed since about 1975[6] with use in fusion reactors as the main impetus. Figure 6 shows a pulsed multipole developed for accelerator use[7]. Figure 7 is a cross section of this source showing a typical magnetic field configuration. These sources have the advantage of being very simple in construction, operate at low pressure (10^{-3} Torr), the plasma can be very stable and they can be made very large. Their main disadvantages are that care has to be taken to avoid holes in the multipole field (loss of primaries to the walls) and that the cathode sheath stability criterion can cause problems with thermionic emitting cathodes. Also the hole problem tends to define a minimum size for the plasma volume.

3. NEGATIVE IONS

Whereas the ions discussed up to now have had a net positive charge, ions with net negative charge have gained popularity in the accelerator field. They were originally used to double the effective energy of electrostatic accelerators by stripping the excess electrons at high potential and reaccelerating the resultant positive ion. Negative ions, whose excess electron is only loosely bound and thus easily removed, are presently being investigated for neutral beam production for plasma heating in fusion research, and for directed energy weapons (Star Wars). The most common use in accelerators is for charge exchange injection from linear to circular accelerators[8)] and for experimental use.

3.1 Surface formation

Historically, negative hydrogen ion sources were modifications of existing proton sources such as duoplasmatrons, with ions extracted from the plasma off the channel axis. The insertion of a floating electrode in the channel of the intermediate electrode greatly improved the production of negative ions (after some dimensional optimisation), and allowed axisymmetric extraction. Furthermore, the addition of caesium to the discharge further increased the negative ion yield. This source was developed to give around 50mA[9)].

The increase in source efficiency with the addition of caesium accelerated the development of higher intensity devices based on the magnetron geometry. It turned out 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 discharge initiating electrode as a support for the caesium coating (pennings, magnetrons, planotrons)[10)].

Research into the mechanism of negative ion production in caeseated discharges has, until now, given little insight into the formation processes involved, but all or some of the three below 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 must be around 0.7 monolayer and that the ion incident energy must be low (a few hundred eV). The importance of the caesium coverage is such that as the duty cycle increases it becomes more and more difficult to maintain that coverage during the discharge. Surface plasma sources of this type are used at a number of laboratories for charge exchange injection. Figure 8 shows a 1A steady state magnetron developed for fusion research.

3.2 Multipole surface source

Unfortunately, the above sources have a poor gas efficiency requiring either large pumping systems or pulsed gas supplies. Some of the problems can be reduced if the plasma generation is made independent of the negative ion production. The fitting into a proton multipole confinement source, of a negatively biased curved converter plate whose radius of curvature was equal to its distance from the extraction aperture, gave extractable negative ion currents which could be increased by the addition of caesium to the discharge[11]. As the pressure in the discharge volume of these sources is of the order of 10^{-3} Torr the gas load problem is greatly reduced but some problems remain in maintaining the caesium coverage.

Any system which extracts and accelerates negative ions will do the same for electrons. Early sources had extracted electron/ion ratios approaching 1000 which required some effort to reduce the accelerated electron currents. Magnetron and similar devices use their stray magnetic field to return electrons to the source. With the converter multipole source, careful arrangement of the electric and magnetic fields around the extraction aperture considerably reduces these ratios. A source incorporating these features is shown in Fig. 9.

3.3 Volume production

Measurements of the negative ions in large-volume, low-pressure hydrogen discharges, gave densities which were much bigger than those predicted by normal theories[12]. Experiments and theoretical studies showed that dissociative attachment of electrons to highly vibrationally excited hydrogen molecules was strongly enhanced as compared to ground state molecules. The addition of a dipole magnetic filter in the plasma volume of a standard multipole ion source enhanced the H^- yield due to this process[13] whilst reducing the electron component. The processes in these sources is believed to be as follows:

a) in the volume between the cathode and the filter, energetic primary electrons (100-200 eV) ionise and vibrationally excite hydrogen molecules,

$$H_2 + e \rightarrow {}^*H_2^+ + 2e \rightarrow {}^*H_2 + e$$

b) excited molecules and cold (low energy i.e., a few eV) electrons diffuse through the filter, which also blocks the high energy primary electrons. Dissociative attachment between the excited molecules and cold electrons occurs in the volume defined by the filter and the end of the source. If hot electrons were to diffuse past the filter, they would quickly strip the loosely attached extra electron (binding energy ~ 0.7 eV).

$$^{*}H_2 + e \rightarrow {}^{*}H_2^- \rightarrow H^- + {}^{*}H$$

Careful choice of the bias of an electrode which closes the front of the plasma volume, and of the operating pressure in the source, reduces the unwanted electron current out of the source to very low values. Good gas efficiency of the multipole and the absence caesium make this source ideal for fusion experiments and accelerator use. Fig. 10 shows a source being developed for the latter application14).

3.4 Double 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 (eg. with caesium):

$$X^+ + Cs \rightarrow X + Cs^+ \quad \text{(neutralisation)}$$
$$X + Cs \rightarrow X^- + Cs^+ \quad \text{(ionisation)}$$

Although this method is falling out of use for high currents because the reaction cross sections fall rapidly with incident particle energy, this technique is used for a polarised negative hydrogen ion source illustrated in Fig. 11¹⁵⁾.

4. MULTICHARGED IONS

The ion sources discussed up to now are generally optimised for singly-charged particles. However, in the ionisation process there is nothing to prevent the removal of more than one electron provided that the incident electron energy is greater than the ionisation potential for that charge state. Two processes can give rise to multiple ionisation:

single step

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

where the incident electron energy is given by the sum of the ionisation energies from state x to state x+n,

or multistep

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

where the electron energy needed is from state n to state n+1. Table 4 gives the ionisation potentials for oxygen.

Table 4. Minimum ionisation energies (eV) for oxygen ions.

Ionisation	0-1	1-2	2-3	3-4	4-5	5-6	0-6	6-7	7-8	0-8
Energy	13.6	35.2	54.9	77.4	113.9	138.1	433.1	739.1	871.1	2043.3

However, in practice, the ionisation cross section rises to a maximum for incident electrons with about three times the minimum ionisation energy and then decreases slowly. The probability of producing multicharged ions by single electron impact falls off rapidly with increased charge state. Thus the only efficient way of achieving high charge states is by successive ionisation, a time consuming process. Charge state distributions in a hot plasma are mainly determined by the ionisation cross section (i.e. the energy of the hot electrons), the electron current density and the exposure time of the ions to the plasma electrons. In general the mean time required to produce a given charge state, $\tau_{n,q}$ is given by:

$$\tau_{n,q} \; . \; n_e \; \alpha \; e \; . \sum_{i=n}^{q} \frac{1}{\sigma_{i-1,i}}$$

where n_e is the plasma electron density. Loss processes working against effecient ion production are electron capture from neutral background molecules, direct capture of plasma electrons and losses to the walls. The plasma density must be much greater than the neutral density and the ion lifetime longer than the mean production time. For acceptable ion production, the product of the plasma electron density and the particle life, or confinement, time $n_e \; . \; \tau$ becomes an important criterion. In the case of light ions it must attain $10^{10} s.cm^{-3}$ for fully stripped ion production with electron energies of less than 5keV. Heavy ions require $10^{13} s.cm^{-3}$ and up to 30keV. By comparison, deuterium-tritium fusion would need 10^{14} and 10 keV.

4.1 Foil strippers

Foil strippers are used to produce multicharged ions. An energetic low-charge-state ion beam passes through a thin foil (μm) which can be imagined to contain a cloud of cold electrons ($\sim 10^{24} cm^{-3}$). Interaction between the ions and electrons occurs during the ions' transit time through the foil (typically 10^{-14}s) giving a $n_e \; . \; \tau$ of the order of $10^{10} s.cm^{-3}$. Step-by-step ionisation of the ions takes place in the foil as well as recombination, but the latter is minimised by the high relative velocity. As only the relative velocities of the electrons and ions count towards the ionisation process, it is the same as outlined above. A thin gas target can replace the foil and in this way a 520keV He+ beam, (equivalent electron energy 70eV), was stripped to produce around 10mA of α-particles 16) . Although the stripping efficiency was probably less than 25 %, the yield was considerably better than could be obtained by direct production in a duoplasmatron. If the target were of the optimum thickness, 100 % stripping would occur at around 1.5MeV incident energy (204eV electrons) 17).

4.2 Electron cyclotron resonance

An Electron Cyclotron Resonance (ECR) source is the inverse of a foil stripper. Cold ions diffuse into a plasma of hot electrons. The only problem is to heat the plasma. In a volume filled with microwaves of frequency W and immersed in a magnetic field, there exists a surface where the ECR condition

$$Wc = e.B/m \quad \text{or} \quad Fc = 2.8\text{GHz/kG}$$

is satisfied. Electrons crossing this surface will, in general, be heated. Also, if the electron-ion collision frequency is of the order of, or smaller than, the ECR frequency, break-down will occur and a plasma will be formed. As long as the plasma frequency, Wp,

$$Wp = \sqrt{(n.e^2/\epsilon_0.m)} \quad \text{or} \quad F_p = 9\sqrt{n}\ \text{kHz}$$

is less than the microwave frequency, the microwaves can penetrate the plasma. Thus the maximum attainable plasma density is given by the microwave frequency, and for 10GHz the density limit would be around 10^{12} cm^{-3}. With the $n_e.\tau$ criterion, ions must be confined for about 10ms. These confinement times can be attained in a minimum B-magnetic configuration.

The MINIMAFIOS source (Fig. 12) works on this principle[18]. The minimum-B field of between 0.2 and 0.5T is obtained by superimposing solenoidal and hexapolar fields, and somewhere in this volume exists a 10GHz ECR field of 0.36T. This resonance can heat the plasma electrons to many keV. Electrons with sufficient energy to produce high charge states would be inefficient in ionising the lower states. Therefore, an additional high pressure stage, optimised for the lower states, is added to the main source and ions produced here are allowed to drift into the main high temperature plasma zone where the much lower pressure (< 10^{-6} Torr) reduces recombination.

This source has produced more than 100μA of an O^{6+} beam at 5.6keV/nucleon with a rise time of about 20ms (fig. 13)[19]. Future developments of the ECR source should produce usable quantitites of S^{12+} and ions of elements up to lead are being investigated. The source's main disadvantage is its large power consumption. Heavier ions demand greater plasma densities, therefore higher microwave frequencies, and hence stronger magnetic fields. Superconducting sources seem to be the only way out of the power spiral.

4.3 The electron-beam source

In the Electron-Beam Ion Source (EBIS), a fast dense electron beam is made to interact with cold ions trapped in an electrostatic well. Ions are retained radially by the potential well in the electron beam and axially by electrostatic mirrors. Ions are expelled from the interaction zone by lowering the potential of one of the blocking electrodes. The electron density is given by the current density (and velocity) of the electron beam. The confinement time is partially at the discretion of the user but must be less than the ion lifetime defined by the neutral background pressure. Ionisation is again a multistep process. The minimum interaction time to produce a given charge state is given by:

$$\tau = 1.6 \ .\ 10^{-19}/(\ J\ .\ \sigma_{a,b})$$

where σ is the total ionisation cross section from state a to b. Thus the most important parameter for reasonable ion production is J. In practice this calls for current densities of the order of $1000A.cm^{-2}$. Normal thermionic cathodes usually give less than $100A.cm^{-2}$, so some form of electron beam compression is needed. A large-area electron beam generated in a field-free area is injected into an abrupt solenoidal field. If the magnetic field is correctly selected, Brouillion flow can be established and the current density increased by factors up to 2000 whilst still maintaining a stable, ripple-free, beam of extremely small radius (<.05mm) 20). Figure 14 is a shows a typical EBIS schematically.

Apart from ion production from rest-gas molecules21), ionised particles from a traditional ion source can be injected into the axial potential well and further ionised by electron bombardment22). Care is needed with the very high current densities involved to control the electron beam, and in most cases the used beam is blown up in a collector downstream of the interaction region in a controlled manner. Beam energy can also be recovered if it is felt to be worthwhile. Most EBIS sources now use superconducting solenoids and can work at the high repetition rates demanded by cyclotrons (up to 1kHz).

5. SOLID SURFACE

The sources described up to now have all used discharges in gases for ion formation. However, in certain cases, the desired ion cannot be produced in a discharge, and two sources which use the properties of solid surfaces will now be described briefly.

In the Field Ionisation Source, a surface exposed to an electrostatic field of the order of $10^7 V.cm^{-1}$ will cause the emission of ions from the rest gas. Further increase in the field strength will cause the emission of ions from the surface. In practice, such fields can only be produced by taking advantage of the large enhancement due to sharp points or edges. Producing and maintaining these points is a major difficulty if the point is the feed material. Ion bombardment of the tip will also reduce its effectiveness. Nevertheless, this method can be useful for producing pA beams of materials which are difficult to ionise. In one application a renewable tip was produced by using a conducting liquid in a capillary tube, the action of the electric field on the meniscus pulling the liquid out into a sharp cone.

Desorption of low ionisation potential atoms from a heated high-work-function surface is used in the Thermal Surface Ionisation Source. For a given temperature, T, the ionisation efficiency, η, is given by the Saha-Langmuir equation for clean surfaces:

$$\eta = 1 + W . \exp \frac{V - \phi}{kt}$$

where k is the Boltzman constant, V the ionisation potential of the atom, ϕ the work function of the surface and W a statistical constant. This relationship also requires the surface to be covered with less than a monolayer of the desired element. With a careful choice of substrate, working material and temperature, this source can be useful for alkali metals but difficulties can arise with poorly volatile materials even at high temperatures.

6. SUMMARY

This review of the technology of some of the ion sources used on modern particle accelerators is by no means exhaustive and is biased towards the interests of the author.

Apart from the references quoted in the text, a selection of papers of general interest is given. However, it should not be forgotten that once the ion source has produced its its particles, beam formation and pre-acceleration is needed before the ions can be put to use.

* * * *

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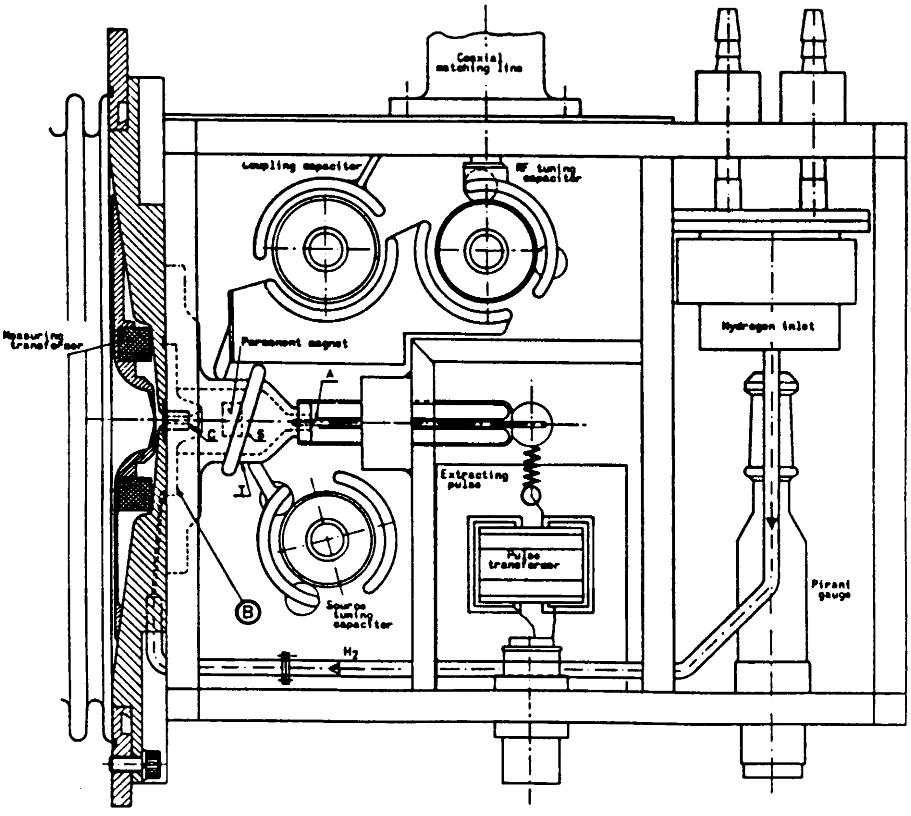

Fig. 1 CERN RF ion source

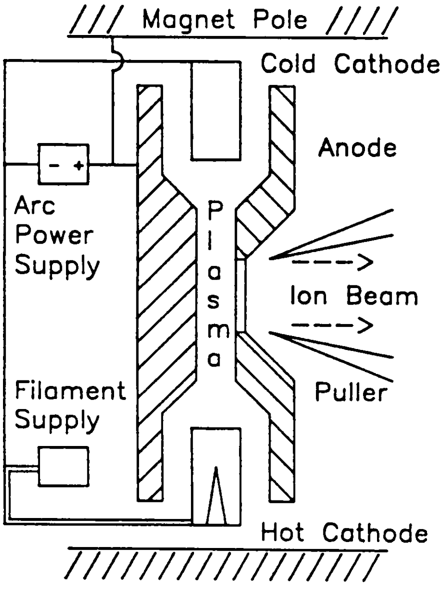

Fig. 2 Schematic hot cathode Penning source

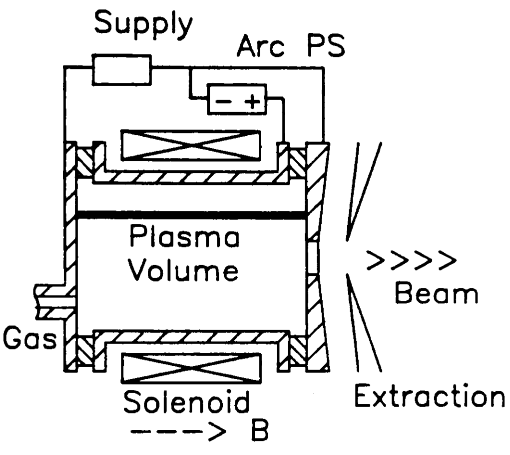

Fig. 3 Axial extraction Magnetron source

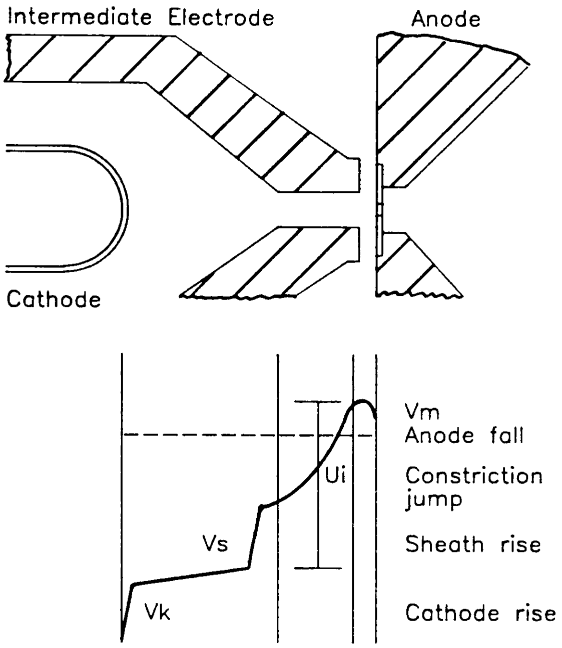

Fig. 4 Idealised potential distribution in the discharge in a duoplasmatron

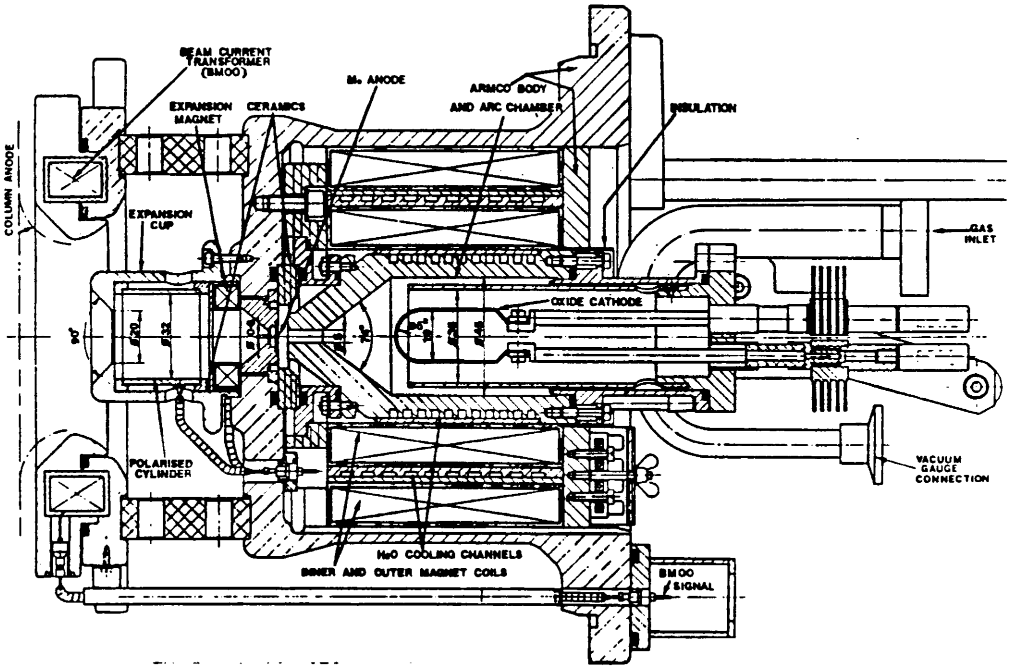

Fig. 5 CERN standard duoplasmatron (with polarised expansion cup)

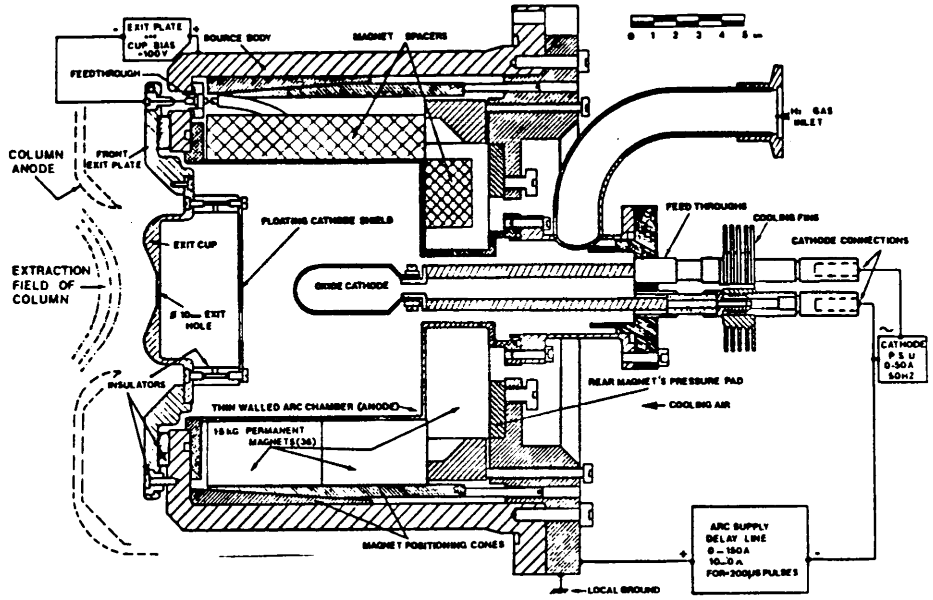

Fig. 6 A multipole confinement small volume positive ion source

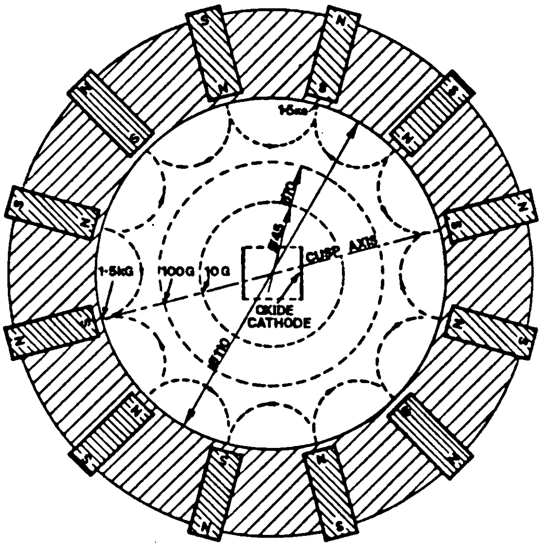

Fig. 7 Magnetic field inside the plasma chamber

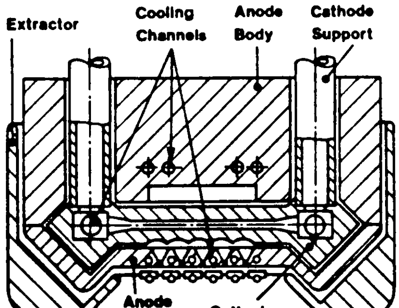

Fig. 8 Cross section of a large steady state magnetron negative ion source

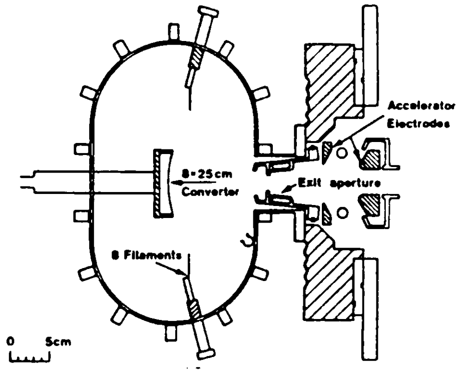

Fig. 9 LBL surface production multipole negative ion source

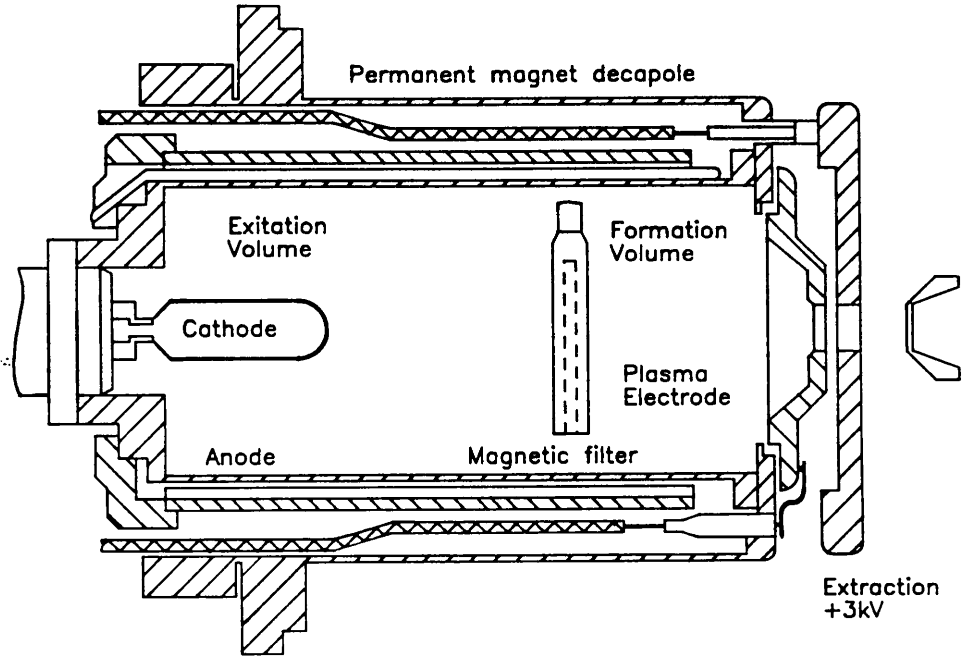

Fig. 10 Prototype volume production multipole negative hydrogen ion source

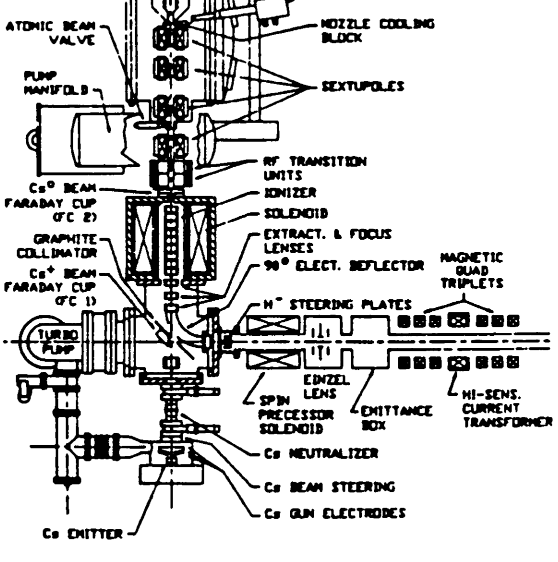

Fig. 11 Brookhaven double charge exchange polarised negative hydrogen ion source

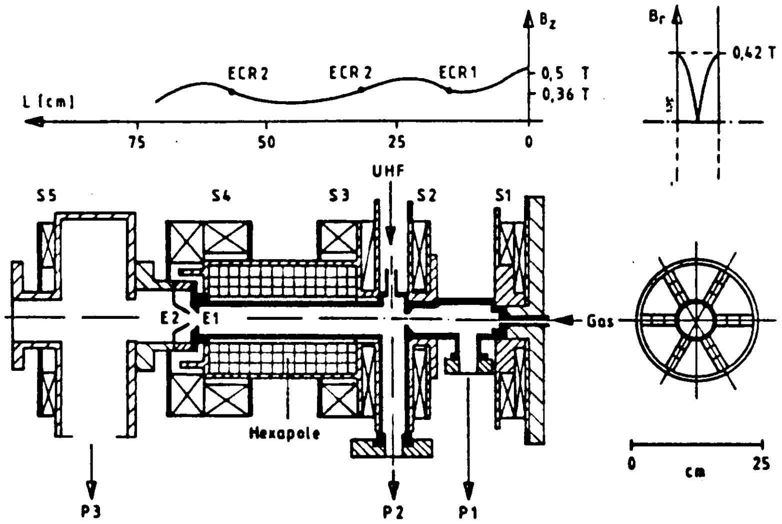

Fig. 12 ECR source MINIMAFIOS; S-solenoids, P-pumps.

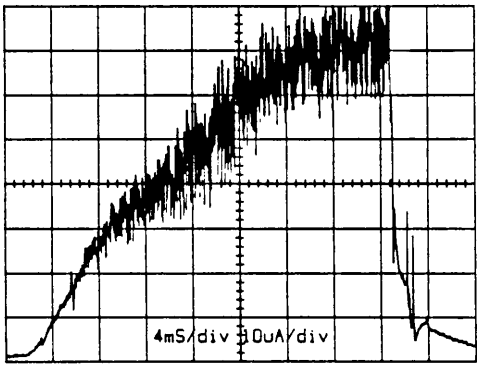

Fig. 13 Typical O^{6+} beam from ECR.

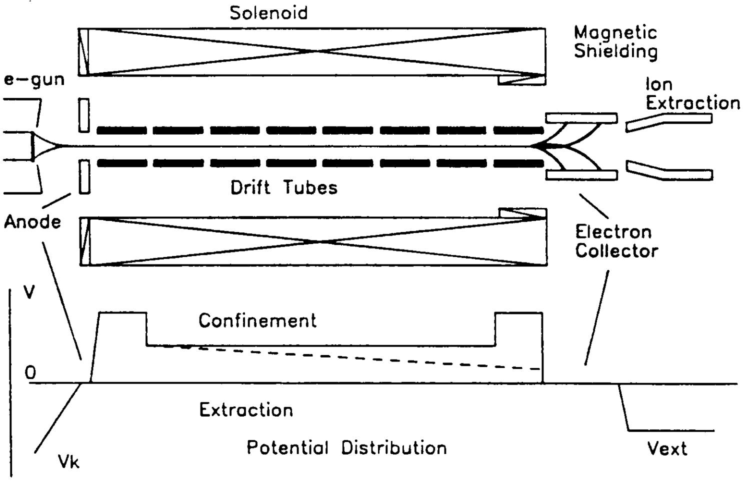

Fig. 14 Typical confined flow electron beam ion source (EBIS)