

Intense H⁺ and H⁻ Sources

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Abstract

The development of intense H⁺ and H⁻ sources is important for present and future accelerator systems, particularly where a low emittance is required. Magnetic multipole sources can meet these requirements and have already been used for many beam applications. However, they are capable of providing more than merely a high current density as the addition of plasma cooling via the effects of internal magnetic fields can modify the inelastic plasma collision processes to provide either a virtually pure H⁺ or H⁻ beam. The magnetic field modifies the plasma transport coefficients such as diffusion and thermal conductivity and leads to electron cooling. This results in a large rate coefficient for molecular ion breakup or dissociative attachment collisions to form H⁻ ions. Many such sources have now been built and key results from these sources are presented including beam emittance studies. The understanding of the plasma behaviour is now quite advanced and modelling results are also described together with comparison with experiment.

1 Introduction

Over the past twenty years there has been a considerable advance in ion source design and in the understanding of their behaviour: This has led to a significant increase in beam brightness, particularly for negative ion sources where a considerable research effort has been made. This paper will not attempt to list the many kinds of ion source which have been developed but instead will focus on the basic physics underlying these developments using an idealised source concept. One type of source, the magnetic multipole source, will be used as an example as it most closely approaches this idealised source.

The objective for an ion source is to produce a uniform homogenous plasma over an area large enough for the extraction aperture (or apertures) with a current density to match the perveance of the accelerator. It is desirable to minimise the power and gas pressure required to produce this current density by optimising plasma confinement consistent with producing the plasma of the correct size. This depends on the source design and below we discuss the merits of the magnetic multipole source which shows this effect clearly. Negative ion sources (such as H⁻ ions) have additional constraints, in particular the need to minimise co-electron extraction and create the right

conditions for negative ion formation. The beam emittance, of the extracted ions is largely determined by the plasma ion temperature which is a function of the discharge conditions.

2 The Idealised Source

The plasma inside a discharge chamber is characterised by confinement time, τ_+ , which is virtually equal for ions and electrons (the electron confinement time in d.c. sources is slightly shorter to allow for the arc current but exact equality exists in rf or microwave discharges). This allows us to write an expression for ion continuity:

$$\frac{n}{\tau_+} = N \langle \sigma v \rangle_i n_e \quad (1)$$

where N is the gas pressure, $\langle \sigma v \rangle_i$ is the ionization rate, n is the plasma density and n_e is the density of electrons which can ionize the gas. The advantage of maximising the ion confinement time, τ_+ , is clear as n is linearly proportional to τ_+ .

The density of n_e and the magnitude of $\langle \sigma v \rangle_i$ depend on the source type. For dc sources n_e is determined by a special group of electrons emitted by the hot wire filaments at an energy roughly equal to the arc voltage^(1, 2). Thus n_e is relatively small compared with n but $\langle \sigma v \rangle_i$ is large and insensitive to the electron energy as it is near to its maximum value at around 100 eV. In rf and microwave sources, the gas is ionised by the plasma electrons so n_e is equal to n and hence is much larger but $\langle \sigma v \rangle_i$ is relatively small. As τ_+ and $\langle \sigma v \rangle_i$ are only functions of the type of gas, the geometry and the electron temperature, in this mode equation 1 only determines the electron temperature; the plasma density is derived by a second relationship arising from energy balance. In dc sources this energy balance relationship determines the electron energy instead.

This latter expression takes the simplified form⁽³⁾:

$$E = \frac{n}{\tau_+} (T + \phi) e \quad (2)$$

where c_s is the ion sound speed and ϕ is the plasma sheath voltage between the source walls and the plasma. The term

E represents power transferred from the external source to the plasma per unit volume. For dc discharges E depends on coulomb collisions and so is proportional to the product n_i and roughly inversely proportional to the 3/2 power of the fast electron energy (or temperature)⁽³⁾. Discharges based on rf or microwave are more complicated as the rf power is coupled directly to the plasma (apart from inelastic losses). The term E must now include other energy links apart from electron energy transfer to the walls. In general rf discharges tend to be hotter than equivalent dc discharges.

The reversal of the roles of the particle balance and energy balance equations also determines the general pattern of behaviour of dc and rf sources. In general dc sources work at lower pressure because of the larger value of the ionisation rate $\langle\sigma v\rangle_i$, but need a cathode structure to emit fast electrons which is also an ion absorber. In hydrogen discharges this effect can be a large loss of ion current⁽⁴⁾, particularly for negative ion sources. As these ionising fast electrons interact only weakly with the background plasma their density shows a weak exponential decay with distance within the discharge chamber so giving a large region of ionisation. On the other hand in rf and microwave discharges the ionisation region is very limited because of the finite electrical conductivity of the plasma which leads to a narrow skin region where the rf driven electron currents flow. Outside this zone no power can be easily transferred to the plasma. Thus the term E above is only non-zero in this region.

The thermal plasma has density gradients arising from the need to transfer the plasma particles from the centre of discharge to the walls via ambipolar diffusion. This diffusion coefficient is constant within this idealised plasma leading to a cosine distribution in cartesian geometry (or bessel function distribution for cylindrical symmetry). These density gradients are of not of great importance if we only require a single beamlet (apart from emittance considerations) but are critical if we need a larger extraction area for a slit aperture or multiple apertures such as those required for fusion applications.

3 The Multipole Source

The generic design of a multipole source is shown in figure 1. It consists of a box shaped chamber which is the anode and also the vacuum chamber. This chamber is covered on the outside by rows of permanent magnets arranged in a N - S alternating pattern as illustrated in the schematic drawing. These magnets provide confinement for the plasma discharge as the intense fields near the wall constrain the plasma electrons and ions to reach the anode only at the magnetic cusps in front of each row of magnets. The loss confinement time is simply defined as:

$$\tau_+ = \frac{V}{A c_s}$$

where V/A is the volume to effective loss area ratio. In unconfined sources A is just the mechanical surface area of the source but unconfinement reduces this area to a significantly smaller value:

$$A = A_x + 4L\rho_h$$

$$= A_x + A_a \zeta/4\rho_h$$

where ρ_h is the hybrid Larmor radius for ions and electrons ($= (\rho_e\rho_i)^{1/2}$) A_x is the extraction area, A_a is the anode area and ζ is the intercusp line separation. The multipole source thus can achieve a considerable reduction in ion loss area, dependant on the value assigned to A_x with a resulting significantly rise in plasma density.

However this is not the only advantage. As the multipole field at the anode has only a short range, the majority of the plasma volume is field free. In this field free region the plasma has its ambipolar diffusion coefficient, D_{∞} , with an associated density gradient given by:

$$\nabla n = -j/eD_{\infty} \quad (3)$$

$$\text{and } \nabla j = e n_i n \langle\sigma v\rangle_i$$

where $D_{\infty} = 2D_i$. The ionic diffusion coefficient, D_i is simply $e\Gamma/mv_i$ where T_i and v_i are the ion temperature (in eV) and collision frequency of the plasma ions. The latter is proportional to gas density. If $n_i \langle\sigma v\rangle_i$ is independent of spatial position this leads to a parabolic density distribution. On the otherhand in rf discharges where n_i equals n we obtain a cosine distribution. However the value of D_i is very much smaller near the walls because of the effects of the magnetic fields in multipole sources. Chen⁽⁷⁾ argues that:

$$D_a = D_{\infty} / (1 + \omega^2/\nu^2) \quad (4)$$

where ω is the cyclotron frequency for electrons and ν is the total inelastic and elastic collision frequency. Even relatively low fields of around 50 gauss are sufficient to reduce D_i drastically.

As a result the plasma density is very homogenous in the field free region but has a steep gradient near walls in

planes orthogonal to the anode wall which has the multipole field. The extraction plane is one such plane. However the plasma is non-uniform orthogonal to the extraction plane and shows a significant fall in density in passing from the back of the source to the field free extraction plane. Fortunately this does not affect transverse beam properties such as emittance.

3.1 Specialised Multipole Sources

This density gradient orthogonal to the extraction plane can be exploited in intense discharges for both positive and negative ions. The addition of a weak magnetic field parallel to one of the axes of the extraction plane and positioned between the ionization region (ie the filaments or antenna) and extraction plane reduces the value of D_{\perp} for motion orthogonal to the extraction plane. As a result a steep density gradient appears with a resulting very high density and hot plasma forming in the ionization (usually called driver) region and a cold dilute plasma forms in the extraction region. This feature can be exploited to form single species positive ion discharges or negative ion rich plasmas. These are discussed below.

3.1.1 Positive Ion Sources

The main problem with molecular gas discharges has been the formation of multiple ion species and high plasma electron temperatures leading to plasma ion heating and a resulting low intrinsic beam emittance. Hydrogen is a good example as direct electron ionization leads to the formation of H_2^+ . Subsequent collisions of this ion with an electron or gas molecule form H^+ and H_3^+ respectively. The same pattern of events is true for other molecular gases such as N_2 or O_2 . This is inconvenient as usually only the atomic ion is required, the molecular ion space charge decreases the effective accelerator perveance, thus limiting the beam current in the desired species (in addition to the simple species fraction effect).

The magnetic field described above (usually called a filter) overcomes this problem^(6, 7) by intensifying the plasma density in the driver region by a large factor (up to 10 fold has been observed⁽⁸⁾ which breaks up molecular ions as this process is proportional to the square of the plasma density. Also the plasma in the extraction region is cooled and fast electrons are inhibited which prevents new molecular ions from reforming by ionization while dissociation to atomic ions can still occur as this is a cold electron process. The PINI plasma source developed for JET neutral beam heating increased its proton fraction from 65% to 90% using this approach⁽⁷⁾ and an illustration of the results is shown in figure 2. Such procedures should work for other molecular gases.

The magnetic filter works by decreasing the electron motion orthogonal to the magnetic field lines. Both the electron diffusion coefficient and the electron mobility are decreased

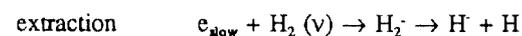
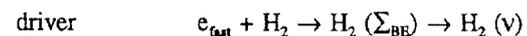
according to equation 4, the only difference being that the value of ω is smaller as the filter field is only around 50 gauss unlike the multipole fields at the plasma edge which can exceed 1 kilogauss. The reduction in mobility also affects thermal transport within the plasma which is also reduced with an end result that the electron temperature near the extraction plane is much smaller and is largely determined by heat flow from the much hotter (and denser) driver region.

The intrinsic beam emittance is determined by finite plasma ion temperature effects⁽⁹⁾ which are largely determined by the heating caused by plasma electrons. The ions are cooled by ion-gas charge exchanging or elastic collisions and the balance between these two processes largely determines the ion temperature. The rms beam emittance in helium discharges where ion - electron coupling is weaker than hydrogen is typically 0.04π mm mrad for a 8mm diameter beam. This corresponds to an ion temperature of 0.5 eV which increases slowly with current density due to inhomogeneities in the plasma. In hydrogen discharges the ion temperature is slightly larger probably because of the Frank - Condon energy.

The magnetic filter helps significantly here as it reduces T_i to about 1 eV in hydrogen discharges and while this strengthens the electron ion coupling it also clamps the ion temperature to a maximum value set by the electron temperature.

3.1.2 Negative Ion Sources

The magnetic filter can be used to form negative ions by dissociative attachment collisions between cold electrons and vibrational excited molecules⁽¹⁰⁾. These collisions have an optimum rate at around an electron temperature of 1 eV which is coincidentally similar to that required for proton production as described above. The hot dense plasma in the driver region, produces significant fluxes of vibrational excited molecules, in addition to ionization, so that the two separate plasma regions each combine to yield a reasonable flux of negative ions. The two stage process can be written⁽¹⁰⁾:



There are also several destruction channels for H^- ions, electron detachment and $H^+ - H^-$ ion recombination being thought to be dominant. The latter dominates for very cold plasmas while the former dominates for plasmas in excess of 2 eV temperature.

Many such negative ion sources have been constructed, mainly for the thermo-nuclear fusion programme where they will be used for neutral beam heating experiments for next

generation tokamaks such as ITER. A modified version of the PINI source has also produced significant current densities of H⁻ ions. However it is small negative ion sources of this type where the technology has advanced the most.

The small source developed at AEA Technology, Culham⁽⁴⁾ has attained 22 mA/cm² of H⁻ in dc operation (44 mA of beam current) and exactly twice these values when cesium is added as a catalyst. A plot of the current density versus discharge current is shown in figure 4 where the difference between cesiated and uncesiated performance is seen. In uncesiated operation the current rises linearly at low arc currents but then begins to saturate at high power levels. This aspect of behaviour is common to all sources of this type and arises from the quadratic scaling with plasma density of ion-ion and electron detachment collisions for H⁻ loss. A low power version of this source is being used by IBA in Belgium for their cyclotron accelerators.

When cesium is added the behaviour becomes linear with arc current and this also is common for all multipole sources. At present the exact cause for the change in behaviour and the increase in H⁻ yield is not fully understood but in our opinion this is created by an additional plasma volume production process possibly auto-ionization of excited cesium and hydrogen atoms.

The emittance of H⁻ ion beams is more complex than analogous H⁺ beams as seen in figure 3. This arises from two causes; the direct effect of weak magnetic fields at the extraction aperture giving rise to a stochastic deflection angle⁽⁹⁾ and an indirect effect caused by the plasma density gradients caused by the magnetic filter which causes a rapid rise with j . The latter effect causes an emittance growth which scales with beam perveance⁽¹¹⁾ and leads to an effective beam emittance that is slightly larger than H⁺ beam values. Even so the effective rms beam emittance is typically 0.15 π mm mrad for the beam currents described above (which corresponds to an ion temperature of about 2 eV).

3.1.3 Electrostatic Accelerators

Acceleration techniques for positive ions are well established and it is not proposed to discuss further this aspect in this paper. However negative ion accelerators have an additional problem caused by the presence of electrons in the discharge plasma. Although the density of these electrons is comparable to the negative ions in the discharge, the electron velocity is approximately two orders of magnitude larger than that of the negative ions so if no suppression is attempted the extracted H⁻ current would only form approximately 1% of the total beam current, not an attractive option!

Fortunately there is a simple solution to this problem. The first stage is to suppress the electron current before

extraction by placing a local magnetic field across the first aperture of the accelerator as shown in figure 5. This again pins the electrons to the field lines as occurs in the magnetic filter and reduces the local value of the diffusion coefficient. However the electrons are free to move along the field lines and preferentially lost on the sidewalls of the beam forming aperture. The extracted electron current density, j_e , falls very rapidly with integrated magnetic flux, F , ($= \int B dz$) so that

$$j_e = j_{e0} \exp \left[- \frac{vF}{8T} \cdot \exp \left(- \frac{\phi}{T} \right) \right] \quad (5)$$

where v is the electron thermal velocity and T is the electron temperature in eV. the parameter ϕ is the potential barrier between the plasma and the beam forming electrode. The above expression shows that it is possible to get around two orders of magnitude attenuation of electron flux.

This is not however sufficient as the electron flux and H⁻ flux are now only equal. A further level of suppression can be achieved by collecting the extracted electrons on a low energy electrode in the accelerating column. This is again relatively straight forward as the electrons are collected by deflection on the second electrode of the accelerator. The beam ions suffer a minor deflection which is corrected by subsequent further deflection fields downstream. For two gap accelerators this collection potential is between 15 and 20% of the final beam energy. Much lower fractional potentials can be obtained by increasing the number of gaps. The final H⁻ beam divergence is not noticeably affected by the fields used to suppress electrons and is typically 0.5°.

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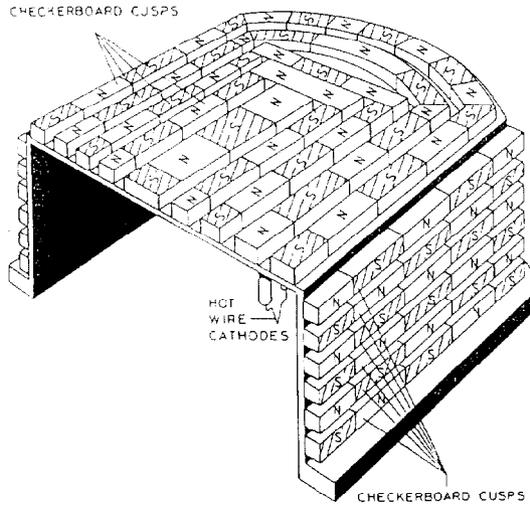


Figure 1

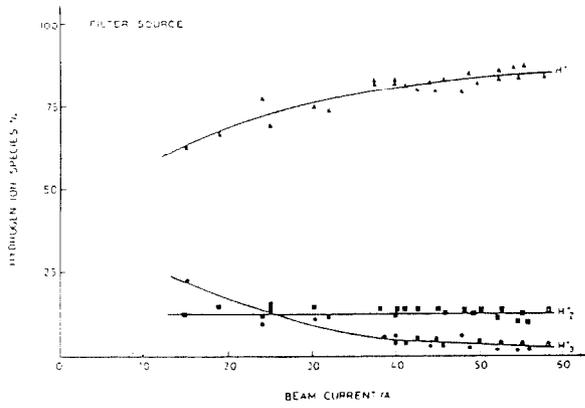


Figure 2a

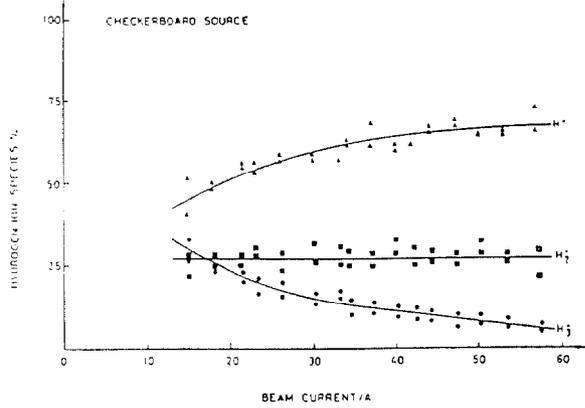


Figure 2b

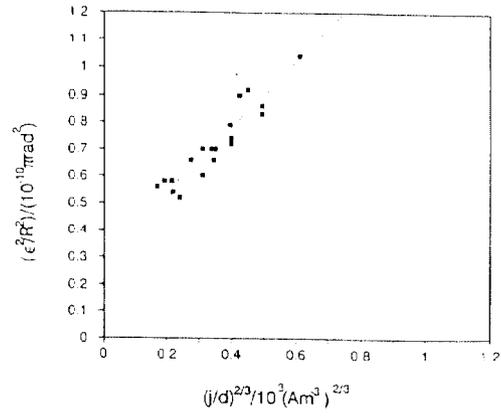


Figure 3a

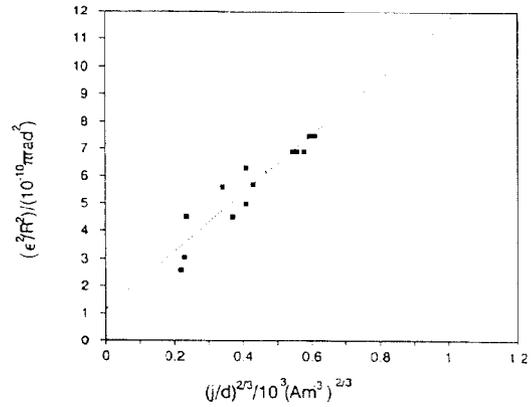


Figure 3b

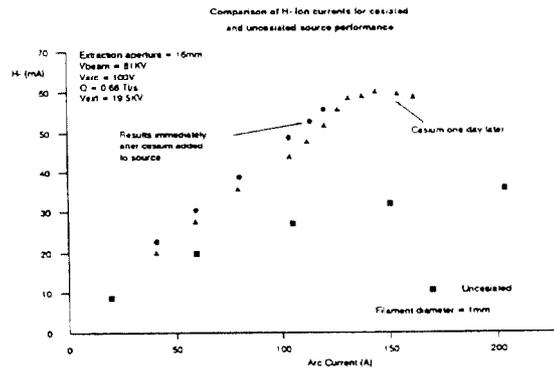


Figure 4a

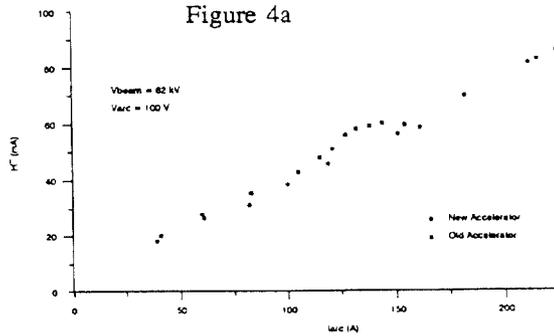


Figure 4b