NEGATIVE HYDROGEN ION SOURCES FOR ACCELERATORS*.

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Abstract

A comparative analysis is presented of different types of negative hydrogen ion sources used in present-day accelerators. Emphasis is mainly given to pulsed sources, as required for the majority of accelerators, but also considered are dc sources which represent the extreme limit of high duty cycle operation. The discussion considers the issue of beam brightness, power efficiency, reliability, life-time and consumption of gas and other consumables. It is concluded that the surface plasma sources offers the best performance for accelerator applications and the possible future development of such sources is discussed.

1. INTRODUCTION

Over the past twenty years charge-exchange injection has developed from the successful pioneering experiments in Novosibirsk [1] and the first application on an operating machine at the Argonne ZGS [2,3] to become the routine and preferred method of high efficiency injection into the majority of present day circular proton accelerators.

This rapid growth would not have been possible without significant progress in the field of intensive H^- ion beam production. This progress was stimulated by the development of the Surface Plasma Method (SPM) [4,5] of negative ion production, which resulted in the successful generation of Surface Plasma Sources (SPS). Surface plasma production is exploited directly as in the SPS or contributes a considerable part to the H^- output in all types of negative ion source used at different accelerators around the world.

Although the main investigations and developments of H^- ion sources [6,7,8] operating at accelerators were carried out some time ago, it has been necessary to have a lengthy period of experience to accumulate knowledge on the operational performance of these sources on accelerators. It is now an appropriate time to summarize and discuss the findings from this period of operational experience. Also the time is propitious because there is now a need for further development. Many accelerators now using charge-exchange injection were built originally with direct proton injection and adapted at a later date. These accelerators and current accelerators designed specifically for charge exchange injection, required H^- beam currents of 20-50 mA, with normalized emittance of ~1 mm mrad and a duty cycle ≤2%. However, with developments for the next generation of high intensity proton accelerators [9], there is a need to improve these parameters with beam current up to 100-150 mA, emittance 0.1 mm mrad or less and with a duty cycle of around 10%.

This paper analyses the current performance of H^- ion sources and the anticipated developments. The issues of beam brightness, power efficiency, reliability, life-time and consumption of gas and other consumables are discussed. It concludes that the surface plasma source offers the best performance for accelerator applications and the possible development of such sources is considered. Unfortunately the shortness of this paper does not permit as detailed a discussion as would be desirable, but familiarization with a good introductory review[10] will help compensate this.

2. GENERAL CONSIDERATIONS

2.1 Basic Principles Of Negative Ion Production

All H^- ion sources currently used on accelerators may be divided into either 'Volume' or 'Surface Plasma' type with respect to the principle method of negative ion production.

Volume production is based on H^- ion formation through particle collision reactions in the gas discharge plasma. The main reactions are dissociative attachment to hydrogen molecules and dissociative recombination of positive molecular ions by low energy plasma electrons. The cross-section for these reactions is quite small $\sim 10^{-20}$ cm^2 [11], but increases to $\geq 10^{-16}$ cm^2 for excited vibrational states, $v > 5$ [12]. However, the higher cross-section decreases with increasing incident electron energy as $\exp(-W_e/T_r)$, where $T_r \approx 1$ eV and is only effective for incident energies <1 eV. This factor together with negative ion destruction reactions limits the rate of H^- ion production. Although theoretical optimization [13] predicts 100-200 mA cm^{-2} for the H^- emission current density, only 20-30 mA cm^{-2} is obtained in practice.

Surface plasma production of ions is by negative ionisation on a metal surface enhanced by the influence of the gas discharge plasma [4,5]. Due to the energy difference between the small electron affinity of a H-atom ~0.7 eV and the relatively large work function of 4-5 eV of the surface at the normal operating temperature the probability of hydrogen forming H^- ions on a metal surface is normally exponentially small. Decreasing the work function, by covering the surface with caesium to a density of ~0.7 of a monolayer, significantly increases this probability. The work function decreases to <1.5 eV and the electron affinity is moved close to the Fermi level. The affinity level of an atom close to the surface may then be occupied by an electron from the conduction band of the metal with a probability close to

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unity. To be stable the ion formed must be moved quickly away from the surface. In practice, the necessary momentum is obtained from energetic particles incident on the surface from the plasma. These are produced by biasing the emitter electrode, usually the cathode of the discharge cell, 100-200 V negative with respect to the plasma potential. The velocity obtained by the ion also helps it to survive transit through the plasma to the emission slit.

2.2 Ion Source Features

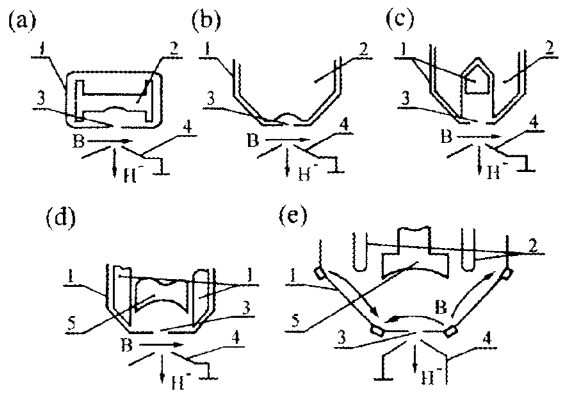

Figure 1: (a) Planatron (Magnetron), (b) Semiplanatron, (c) Penning Independent emitter types: (d) Penning discharge, (e) Multicusp. 1-anode, 2-cathode, 3-emission aperture, 4-extractor, 5- negative ion emitter.

Simplified diagrams of five different types of present day accelerator H^- ion sources are shown in Figure 1. In sources (a), (b) & (c), a self-sustained discharge is obtained in crossed electric and magnetic fields and H^- ions are produced on the cathode of the discharge cell and extracted through an aperture in the anode. In the magnetron the plasma drifts round the central cathode (closed drift), but in the semiplanatron the drift is restricted (unclosed drift).

In sources (d) & (e) a separate negative ion emitter is used, which is biased 100-200 V negative with respect to the plasma potential. Plasma generation in (d) is by a Penning discharge and in (e) by either a hot filament or RF excitation. H^- ions are extracted through an aperture in the anode. These sources may be converted to volume production by removal of the emitter electrode.

Sources (a), (b), (d) & (e) rely on the principle of direct extraction of surface produced negative ions. In the Penning source (c), the ion beam is mainly formed from H^- ions created from a resonant charge exchange reaction between the energetic surface produced H^- ions with slow H-atoms thermalised by collisions with gas molecules and the chamber walls. H^- surface production may be enhanced close to the emission aperture, but this increases ion temperature..

Sources (a), (b) and (c) are known as Surface Plasma Sources and may be distinguished from sources (d) & (e) by their high emission current density capability of >1 A cm^{-2}. The volume sources (VS) like (d) & (e) were developed for fusion research applications from adaptations of the fully developed positive ion sources, but their emission current capability does not exceed 200 mA cm^{-2}.

Gas consumption is directly dependent on the operating gas pressure and the emission aperture area. Consumption in the SPS and VS is similar since the higher emission current density of the SPS compensates for its relatively high pressure of 100 mTorr compared with 1 mTorr in the VS.

However, for pulsed operation consumption becomes strongly dependent on the discharge cell volume. Stable operation of the source requires a certain ionisation thickness defined by the product of the gas density and ionisation path length for energetic electrons. As a first approximation this parameter is independent of the type of discharge cell. Since the ionisation path length is proportional to any characteristic dimension of the discharge cell, L, gas consumption increases as L^2. The SPS is preferred in this respect, because it has a very small discharge cell compared with the VS. With low gas consumption it is possible to design a fast acting gas valve [15], allowing the SPS to run at up to several hundred Hz with a consumption of 1 Torr cm^3, whereas the VS operates CW or at low repetition rate.

The above argument is also valid for the consumption of caesium with the added constraint that whilst the plasma is fully ionised the caesium is completely confined to the cell, limiting the flux for a SPS to ~4 ng per pulse.

Power efficiency is defined as the ratio of discharge power to H^- output. In the output range 10-50 mA efficiency is ~100 W/mA and is similar for both the SPS and VS. But this definition does not take into account the power for the emitter electrode, filament or RF generator and the additional extractor power required for electron loading. The VS has an e^-/H^- ratio of 30-50 compared with the SPS ratio of $\sim 1-2$.

The semiplanatron is the most efficient of the SPSs, about 1.5-2 times better than the magnetron. In the range of discharge current of 20-30 A the semiplanatron is 5-7 times more efficient than the Penning, but at higher currents these sources become equivalent. In the magnetron the H^- current shows saturation at ~100 A discharge current and then falls away whereas the Penning is still effective at discharge current densities up to 300 A cm^{-2}.

Beam brightness is determined by the ratio of the emission current density to the ion temperature on the emitter surface (solid or plasma.).

Surface produced H^- ions have large angle and energy distributions resulting from energetic bombardment from the plasma, sputtering and backscattering processes. This is confirmed experimentally [17] from which an ion temperature of 10-15 eV is obtained. The Penning has a far lower temperature ≤ 1 eV, determined by the resonant charge exchange mechanism. This is confirmed by ion emittance [18] and ion temperature measurements [19]. Thus for the Penning the high current density and low ion temperature results in a higher brightness.

3. PROBLEMS & POSSIBLE IMPROVEMENTS

A brightness of 8 A/(mm mrad)^2 has been obtained [18] for a 40 mA H^- beam, but requires empirical skill in optimisation.

The main cause of beam degradation results from multi mode oscillations in the discharge at frequencies ranging from tens of kHz to tens of MHz. The nature of these oscillations is not understood and needs further study. Recent results show that some oscillations can be damped by fitting suitable electronic filters close to the source electrodes, leading to plasma density stabilisation and more stable extraction conditions in penning type discharges where ions are collected from the plasma boundary.

Ion extraction conditions are also important to beam quality. The plasma boundary is subject to the continuity condition that the local density of ion flux to the boundary from the plasma side must equal the extracted flux forming the beam. This follows from the principle that the electric field on each side of the boundary must be zero and the initial ion velocities are zero or very small. Beam optimisation requires adjusting the H^- ion density to maintain this equilibrium for each extraction geometry and voltage. This is possible in the Penning , but is more difficult in magnetron and semiplanatron sources. In these sources H^- ions arrive at the plasma boundary with relatively high energy and collected by the extraction field penetrating the boundary. Since behind the boundary there is no field as the plasma is quasi neutral a strong electrostatic lens effect is produced with significant spherical and chromatic aberrations.

Emittance growth may also occur in the focusing and transportation after extraction. This results from the need to space charge neutralise the beam with positive ions produced by beam ionisation of the residual gas. The optimum neutralisation is a positive ion density slightly lower than that of the H^- ions so that slow electrons are expelled from the beam. If the positive ion production rate is greater than its loss rate, over compensation occurs and electrons accumulate in the beam region forming a residual gas plasma leading to plasma instabilities and growth in the H^- beam emittance.

Axial extraction is desirable for high brightness beams, but the majority of operating SPSs use slit apertures. This is to reduce aberrations resulting from the need for large aperture area to produce the high current and also to reduce the e^-/H^- ratio. However, this has the disadvantage that it results in a non equilibrium distribution in transverse beam velocities when the ribbon beam is transformed into one of circular symmetry. During subsequent acceleration and focusing the beam is equilibrated and the initial high brightness is lost. Estimates based on present experimental data indicate that it should be possible to obtain 100-150 mA H^- beam with axial extraction from a SPS with an acceptable e^-/H^- ratio and an emittance of ≤ 0.1 mm mrad.

Duty cycle and lifetime are interrelated and depend on the power to the electrodes Sputtering, particularly at the cathode is the limitation. As a first approximation the product of power load, duty cycle and lifetime may be assumed constant. The last two factors determine the total operating time, equivalent to CW operation.

The VS was developed as a CW device and due to their relatively low discharge parameters has a lifetime of a few hundred hours. This may be improved by using lanthanum hexaboride filaments or RF excitation to drive the discharge.

Initially it was assumed that the lifetime of an SPS was limited to ~1000 h at 2% duty cycle by sputtering of the cathode intensified by caesium bombardment. Operating experience of these sources shows that lifetime is limited by erosion of the electrode behind the extraction aperture (anode in Penning source and cathode in magnetron). The erosion is produced by positive ions from residual gas ionisation being accelerated across the extraction gap into the source and limits the total operating time to 5-10 h.

The majority of SPSs on accelerators use a cold box to prevent the caesium flux into the downstream accelerator. This produces a conductance limitation allowing a high density of gas to accumulate in the box during the pulse. Estimates show that the pressure may exceed 1 mTorr, enhancing the positive ion flux in to the source. The lifetime may be improved significantly by removal or redesign of the cold box together with increased vacuum pumping speed. The positive ion flux to the source may also be reduced by inserting an electrode into the extraction gap biased positive to the ion beam potential.

The duty cycle of a surface plasma source is limited by cooling efficiency. A power density of 10 kW cm^{-2} may be achieved, with ~70% being extracted from the cathode. The magnetron cathode is difficult to cool and this restricts its duty cycle to ~0.1%, whereas the semiplanatron and penning can be cooled more easily and the penning has operated at up to 2% duty cycle.

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