ION-SOURCE AND LOW-ENERGY BEAM-TRANSPORT ISSUES FOR H^- ACCELERATORS*

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Abstract

H^- ions are being used in high-energy accelerators and spallation neutron-sources because of the efficiency with which they can be converted into protons at high energy, a mechanism utilized in schemes that provide injection into a ring by means of charge. This paper discusses new trends and recent developments in the field of H^- plasma generators, extraction systems, and Low-Energy Beam-Transport (LEBT) systems, with emphasis on low-emittance systems delivering beams in the 50-mA range.

1 INTRODUCTION

H^- ion beams have been utilized for many years with high-energy accelerators that include a synchrotron or storage ring because charge-exchange injection is an elegant way to eliminate the problems associated with extreme ramping requirements for injection kickers encountered with positive-ion facilities. Accelerator based spallation neutron-sources are likewise taking advantage of the property of H^- ions to efficiently undergo charge exchange into protons at energies up to a few GeV. Historically, magnetron-type [1] and H^--Penning-type [2] ion sources were the first ones to generate intense beams for this kind of accelerators.

A completely different line of H^- sources was developed in neutral-injection systems for magnetically confined fusion plasmas. These multi-cusp, or "bucket" sources were derived from proton sources when the desired beam energies started exceeding the 100-keV level where the charge-exchange process from protons to neutral hydrogen atoms is less efficient than the one from H^- to neutrals. Substantial progress has been made in the neutral injection field with the understanding of extraction and beam-formation processes in general, including beam transport and space-charge compensation phenomena. This knowledge is by now making its way into the former fields, leading to novel designs of accelerator front ends.

A review paper on H^- ion sources [1] has been recently published, covering a larger variety of source types and providing a useful general background. The present paper is narrower in focus and discusses recent work with H^- ion sources, and Low-Energy Beam-Transport (LEBT) systems, mostly involving bucket sources that are, or are planned to be, installed in spallation-neutron sources and high-energy accelerators.

Since the term "ion source" is subject to some ambiguity because it may or may not include an extraction system we will here distinguish between plasma generators that create the ions and extraction systems that provide beam formation. Extraction systems will be discussed in a separate chapter.

*Work supported by the Director, Office of Science, Office of Basic Energy Sciences, of the US Department of Energy under Contr. No. DE-AC03-76SF00098.

2 PLASMA GENERATORS

There are two basic mechanisms that lead to the generation of H^- ions, i. e., surface and volume production.

2.1 Surface Production Generators

Surface production essentially relies on the small electron affinity of alkaline metals, especially cesium, and plasma generators utilizing this mechanism have some or all inner surfaces coated with a cesium layer. Two representatives of this class are the magnetron and H^--Penning sources mentioned above. Maintaining an adequate cesium coverage, especially at higher duty factors is one of the challenges seen with these devices.

Another variety of surface-production H^- plasma generators [4] is lined with an external multi-cusp magnet configuration that ensures stable and quiet plasma confinement. The discharge is filament driven, and a converter electrode in the center of the discharge vessel is covered with cesium and biased by about -300 V with respect to the plasma potential. The converter attracts positive ions that are abundantly created in the hydrogen discharge, changes a fraction of them into H^- ions, and pre-accelerates and at the same time focuses them towards the outlet aperture. Figure 1 shows a schematic of these sources. A recent converter source [5] is quoted as generating 47 mA beam current at 12% duty factor, with 7.8 kW discharge power. In this device, the axial position of the converter electrode can be optimized on-line, and the discharge-chamber walls are designed to run at approximately 100° C, so as to impede condensation of cesium.

2.2 Volume Production Generators

Volume production of H^- ions relies on a very special plasma condition where vibrationally excited H_2 molecules are exposed to a flux of cold electrons and converted into atoms and H^- ions by dissociative electron attachment or H_2^+ and H_3^+ ions undergo dissociative recombination, again leading to H^- ions [6]. Unfortunately, this plasma

0-7803-5573-3/99/$10.00@1999 IEEE.

condition is not generally encountered in discharges that would produce high particle densities, suitable for the creation of intense ion beams. By separating the discharge plasma into two varieties, however, it became possible to consolidate these two contradicting requirements. This separation is achieved by introducing a magnetic dipole filter into the discharge vessel; only cold electrons and all ions can penetrate this filter at considerable rates, whereas faster electrons that are produced in the main chamber and sustain its plasma are repelled [7].

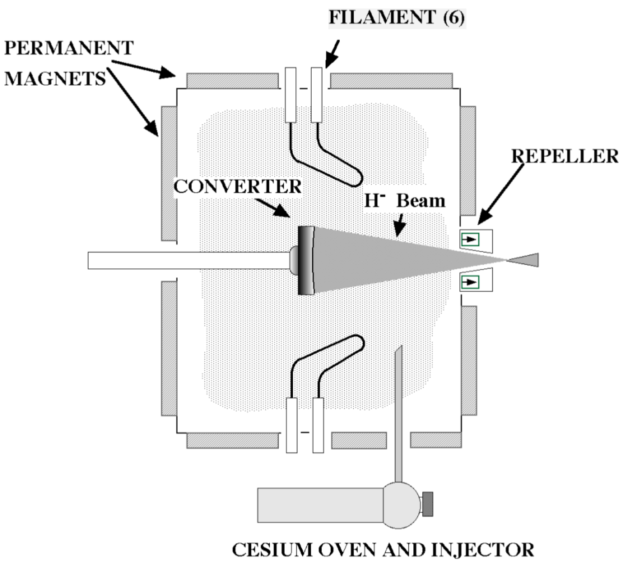

Figure 1. Schematic of a filament-driven converter plasma generator of the LBNL type [5]. The repeller electrode carries magnets that impede electrons from leaving the discharge vessel.

Volume-production H^- discharge-vessels are usually lined with multi-cusp magnets as well, offering the same benefits as in the case of converter devices. Recent versions of this plasma generator type, however, utilize rf power of 2 or 14 MHz frequency instead of filaments to maintain the discharge [8]. The power is coupled to the discharge by an internal antenna, using a variable impedance-matching network that can be adapted to the required plasma density.

Addition of a minute amount of cesium to the chamber surfaces near the outlet aperture enhances the production rate of H^- ions by about a factor of four, proportionally reducing the power needs to achieve a given beam intensity [9]. This technique in essence combines surface and volume production processes and also significantly reduces the electron density in the discharge, mitigating the electron-dumping problem that will be discussed below in more detail.

A schematic of a cesium-enhanced, rf driven, multicusp H^- ion source is shown in Fig. 2. One specimen of such a source is reported to have achieved 45 mA beam current at 6% duty factor from a 6.2-mm diameter outlet aperture [10].

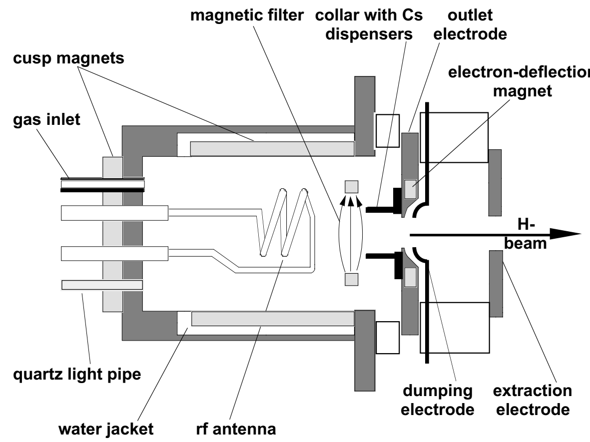

Figure 2. Schematic of an rf driven H^- ion source.

In principle, rf discharges offer higher lifetimes than those found with filament-driven plasmas because the rate of the sputtering process to which the thermionic filaments are subject can be reduced by covering the rf antenna with an insulating coating such as porcelain. Good electrical conductivity between metal and plasma is not needed in the case of an rf antenna. Application of such a coating, however, appears not yet to be fully controlled in all cases, and antennas used in rf-driven plasma generators have shown a wide range of lifetimes [3].

A significant improvement in antenna lifetime (2800 hours operation at 0.05% duty factor without any sign of wear) was achieved by widening the coil, thereby moving the conductor close to the discharge-chamber wall, and covering the entire coil on its inner perimeter by an alumina screen [3].

One research group has recently reversed the main trend for H^- plasma generators, exchanging their rf antenna for conventional thermionic filaments to drive a cesium-enhanced discharge in a multi-cusp vessel. The ion source and diagnostic layout is shown in Fig. 3. A beam current of 120 mA from is reported to be extracted from a 10-mm diameter aperture, when operating a 47.5-kW discharge power at 6% duty factor [11].

3 BEAM EXTRACTION

3.1 Electron Suppression

Extraction of a negative ion beam from a plasma presents a peculiar challenge not encountered with positive ions because large amounts of electrons are being extracted as well, and their space charge tends to deteriorate the quality of the ion beam. Furthermore, these electrons form a particle beam of substantial power that drains the extraction power-supply, and whose power load has to be absorbed by a target electrode. Accelerator H- ion sources therefore use various kinds of magnetic field configurations to suppress these electrons.

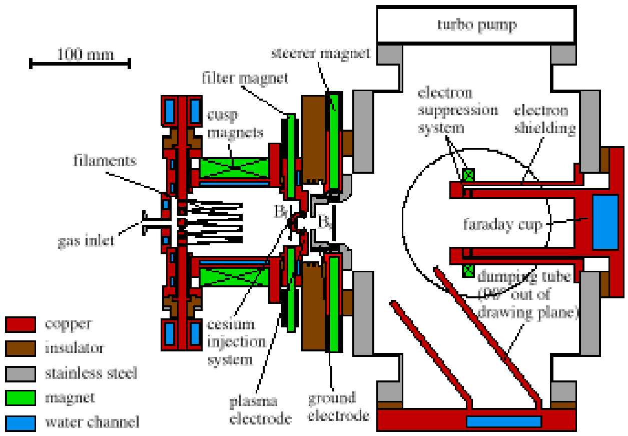

Figure 3. Layout of the Frankfurt H^- source with electron dump and Faraday cup.

Magnetic suppression can be achieved either at full beam energy, separating the electrons from the ion beam somewhere downstream of the extractor electrode as illustrated in Fig. 3, or by repelling them still within the discharge plasma itself. The latter way is being used in converter sources where one can take advantage of the higher ion energy provided by the converter bias-voltage. For volume-production sources, suppression of the electrons in an area where the ions have extremely low velocities would lead to serious problems with space-charge density, essentially inhibiting the formation of high-quality beams.

In a recent approach [10], the electrons are deposited on an intermediate, "dumping" electrode in the main extraction gap near the outlet electrode, as shown in Fig. 2. The separation of the electrons from the ion beam is achieved by inserting permanent magnets in the outlet electrode that generate a transverse dipole field in a location where the ions have already acquired some elevated speed. With this arrangement, the electrons can be entirely removed from the ion beam and deposited at the comparatively low energy of 5 keV.

Utilization of an electron-dumping field has its own price because this field exercises a weak steering action on the ion beam. This action could in principle be counteracted by yet another magnet field, but the simpler remedy consists in mechanically tilting the entire plasma generator with respect to the ideal beam axis through the adjacent LEBT. Model calculations let expect that no offset is needed, additionally to the tilt, to steer the beam onto the ideal axis [10]. The first ion source that is being built on the base of these calculations will have an adjustable tilt angle to avoid having to rely on code predictions.

3.2 Beam Simulation Issues

Apart from the steering angle introduced by the electron-dumping field, extraction systems for H^- ion-beams in general are rather conventional. Unfortunately, to this date there is no widely accepted code available that would allow simulating all essential physical processes that occur during the formation of an H- beam being extracted from a plasma. However, there are again two basic ways to deal with this problem, both involving the use of simulation codes for positive ions.

In the simple approach, the purpose of the calculations is reduced to minimizing the ion-optical aberrations of the extraction, or LEBT, system under the full space-charge load of the expected beam current. This approach appears to be more promising when the ions enter the extraction region already with considerable energy, as is the case with a converter source, because then the trajectories will be less influenced by the exact shape of the plasma meniscus that cannot be properly simulated. Examples of extraction/LEBT systems developed according to this principle are given in Refs. [12] and [13], applied to the plasma generator shown in Fig. 1. Results of beam simulations from Ref. [13] are displayed in Fig. 4.

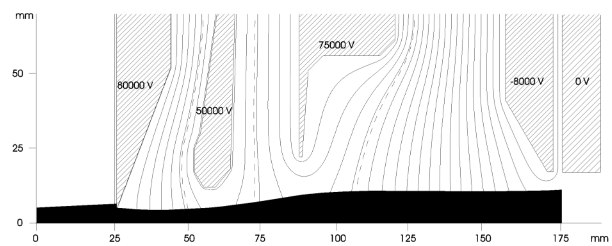

Figure 4. Optimized extraction/LEBT configuration for the LANSCE plasma generator, based on beam simulations using the code IGUN [14]. Electrode potentials as marked in this figure apply to a positive ion beam.

A more refined method makes new use of the fact that many modern simulation codes allow splitting the problem under investigation into smaller parts, with the aim of enhancing the resolution in more critical areas while not making excessive demands on computer memory and processing times where it is not warranted. Trajectory data obtained at the border of the first area are simply transferred as initial conditions into the subsequent area. In the case of negative-ion extraction from a plasma, the full ion and electron space-charge (electrons are best represented by their proton-current equivalent) is being considered in a zone near the outlet electrode, and trajectory data as well as equipotential shapes are computed.

The border between this zone and the subsequent one is chosen at a location where complete removal of the electrons from the ion beam can be reasonably assumed. In the second part of the problem, only the ion-beam space-charge is considered to be present [15].

With this method, even results from different codes can be merged, for example, introducing trajectories obtained from a 3-d code that is able to accommodate the influence of a magnetic electron-dumping field into a simpler one that assumes cylindrical symmetry of the investigated problem, with the benefit of higher resolution and greater speed in the latter part [10].

3.3 Current Measurements

One diagnostic issue related to extraction systems deserves careful attention, i. e. measurement of the extracted beam current in a Faraday cup. In the presence of an intense electron population within the beam, it is very easy to underestimate the danger of measuring electrons together with the negative ions, or of not fully suppressing secondary electrons. A simple validity check can be performed by operating the H^- plasma generator with helium gas, while still using a positive extraction voltage [10]. In this case electrons only will be extracted because helium does not form negative ions, and no signal should be measured in the cup if the electron separation from the main beam works as intended.

4 LEBT SYSTEMS

Low-Energy Beam-Transport (LEBT) systems for the ion sources under discussion usually have to perform multiple tasks. Their main function is to match the extracted H^- beam into the subsequent accelerator structure, such as an RFQ or a high-voltage column, giving the beam the desired radial size and angle. To be able to handle a variety of input conditions and allow empirical tuning to optimize the beam transport downstream of the LEBT, a wider range of decoupled matching parameters is convenient, but it requires at least two independent lenses. At the same time, the LEBT should include some beam-steering elements which may be magnetic, electrical, or simply of mechanical nature and provide adjustments of axis offset and tilt angle.

Facilities where the beam ultimately has to be extracted from a ring accelerator at GeV-level energies, such as spallation neutron sources, use beam chopping to avoid excessively activating their extraction septum. In view of the fact that a considerable fraction of beam is separated from the useful portion and has to be deposited somewhere, the main chopping function is most conveniently performed in the LEBT where the beam power is lowest, leaving the clean-up task where pulse flanks with nano-second-range rise and fall times are shaped to some other beam-line structure.

As another set of requirements, a variety of diagnostics, notably of current and emittance, may be required from the LEBT in order to fully characterize the low-energy beam before it is injected into the subsequent accelerating structure.

Last not least, efficient pumping of the gas emitted from the plasma generator has to occur in the LEBT, the first place in the entire accelerator system where it can be performed. The art of the LEBT designer consists in fulfilling all these demands while keeping the beam emittance from growing excessively. And, in fulfilling those tasks, compromises have to be made sacrificing less important features for the really essential ones.

4.1 Magnetic LEBT

The classic LEBT configuration for high-current ion beams easily reaches 1-m length or more and essentially consists of wide-bore magnetic lenses such as solenoids or quadrupole multiplets, diagnostic chambers, and vacuum pumps. The possibility of obtaining complete space-charge compensation in these structures by bleeding in a controlled amount of auxiliary gas used to be the desirable feature that led to this choice, allowing for relatively modest focusing-strength requirements.

Designers of H^- beam lines have adapted this concept, but the recent trend with beam currents around 40 mA goes towards much shorter structures. Apart from severe emittance growth, one problem will occur as soon as fast-rising pulse flanks are needed because of the finite time it takes to establish full space-charge compensation. Those parts of the beam whose space charge is not fully compensated will be focused differently than the main part and will be lost along the subsequent transport line.

A magnetic test LEBT using two solenoids [16] is shown in Fig. 5. This LEBT is rather short, and its diagnostic elements are supplemented by several instruments installed in a separate diagnostic chamber at its exit. In an operational beam line, insertion of such a chamber would severely degrade the beam quality; therefore it could only be used during commissioning, but this is a price to be paid in any case when highly efficient transport structures for high-current, high-brightness beams are designed. In this LEBT, compensating particles can be removed by six clearing electrodes.

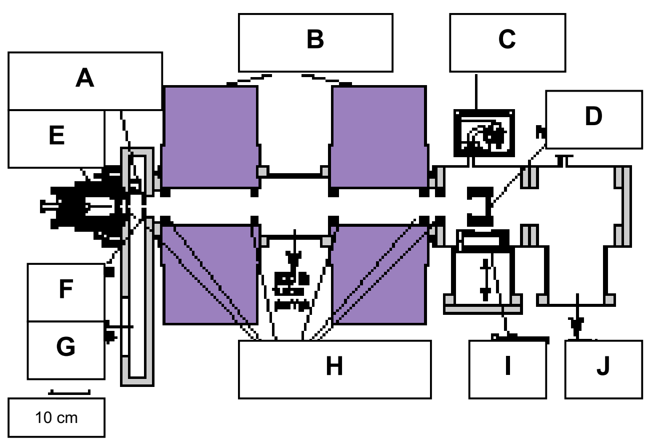

Figure 5. Short magnetic LEBT. A, Faraday cup, profile monitor. B, solenoids of 0.73 T, maximum. C, residual-gas ion-energy analyzer. D, Faraday cup. E, ion source. F, beam scraper. G, 500 l/s turbo pump. H, clearing electrodes. I, emittance scanner. J, 500 l/s turbo pump. A 200 l/s turbo pump is installed between the two solenoids.

4.2 Electrostatic LEBT

From a particle-optical standpoint there is not too much difference between magnetic and electrostatic lenses; a variety of design tools is available to optimize the geometrical shapes of either kind. Some practical issues, however, can determine a choice of one over the other. Electrostatic LEBTs can be built as “open” configurations, providing larger cross-sectional area for pumping than magnetic LEBTs. On the other hand, frequent sparking used to be a serious draw back associated with electrostatic transport systems that have to approach breakdown limits to achieve the intended properties.

Beam simulation codes are again helpful in developing optimized electrostatic structures that fulfill the optical requirements without compromising operational performance.

Fig. 6 shows a very compact electrostatic LEBT [17] designed for the Spallation Neutron Source presently under construction. Its main features include extraction at 81 kV for a final beam energy of 65 keV and two lenses separated by a ground electrode, with the second one being split into four isolated quadrants to facilitate dc steering as well as beam chopping with about 50-ns rise time [18]. The last of the electrodes acts as target for the chopped beam portions and is split into four quadrants as well, allowing to measure transverse beam offset on-line. To compensate for transverse offset against the ideal beam axis, the entire LEBT can be mechanically shifted with respect to the subsequent RFQ structure.

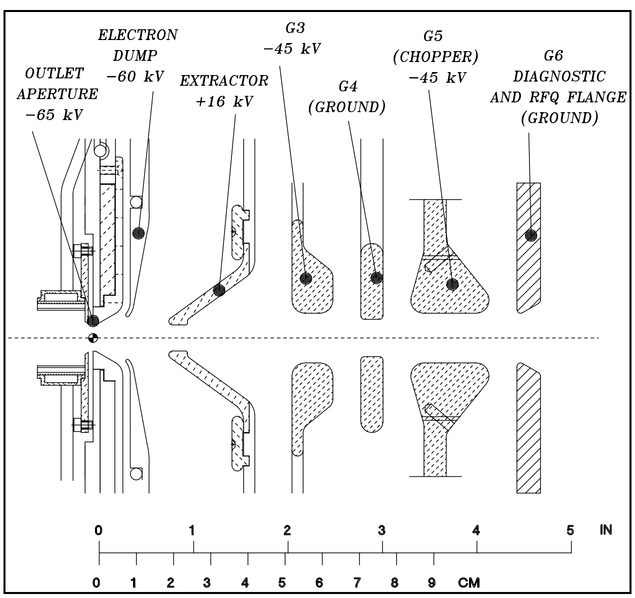

Figure 6. Electrostatic SNS LEBT [17].

5 ACKNOWLEDGMENTS

A major part of the material presented in this paper is related to the author’s work for the Spallation Neutron Source (SNS) project. It is a pleasure to acknowledge the help received from all members of the SNS Front-End Systems group at LBNL, in particular from R. A. Gough and K. N. Leung. Thanks are further due to H. Klein of IAP Frankfurt/Main, Germany, for contributing copious original material.

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