Nuclear Inst. and Methods in Physics Research, A 895 (2018) 150–157

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A 60 mA DC H⁻ multi cusp ion source developed at TRIUMF

K. Jayamanna *, F. Ames, I. Bylinskii, M. Lovera, B. Minato

TRIUMF, 4004 Wesbrook Mall Vancouver BC, Canada V6T2A3

ARTICLE INFO

Keywords:
Ion source
Cyclotron
Accelerator
Medical application
Fusion research

ABSTRACT

This paper describes the latest high-current multi cusp type ion source developed at TRIUMF, which is capable of producing a negative hydrogen ion beam (H^-) of 60 mA of direct current at 140V and 90A arc. The results achieved to date including emittance measurements and filament lifetime issues are presented. The low current version of this ion source is suitable for medical cyclotrons as well as accelerators and the high current version is intended for producing large neutral hydrogen beams for fusion research. The description of the source magnetic configuration, the electron filter profile and the differential pumping techniques given in the paper will allow the building of an arc discharge H^- ion source with similar properties.

1. Introduction

Short-lived radioactive isotopes produced from cyclotrons [1] are now used in medical procedures and research [2–5]. There are over 50 million procedures done during 2017 using existing cyclotrons [6–8]. The usage of radioactive isotopes is growing rapidly, and the number of medical procedures involving radioactive isotopes is expected to pass 450 million procedures annually by 2030 and about 3000 more new cyclotrons would need to be built and installed in or near urban centers all over the world.

One of the major components of the cyclotron is the ion source. In developing the design of cyclotrons for protons or deuterons, negative ions are favored [9] over positive ions due to the charge-changing ability of the energetic beam. While going through a stripping foil placed at the perimeter of the cyclotron, the H^-/D^- change to H^+/D^+ prompts a change in the beam trajectory to shift outwards due to the reverse Lorentz force. The change of the beam trajectory outwards simplifies the beam extraction out of the cyclotron, where a strong magnetic field is present and extraction is otherwise very difficult. After the ejection, the beam can be transported further out of the cyclotron through a beam line to irradiate single or multiple targets to produce short-lived and long-lived radioactive isotopes. While low intensity cyclotrons use H^- ion sources installed in the center of the machine (internal ion source) [10], all high and medium current cyclotrons use ion sources installed outside of the machine (external ion source) [11,12].

Cyclotrons developed by manufacturers like ACSI, BEST, and CYCIAE employ ion sources installed outside of the cyclotron and inject H^- beam through axis; hence, they can deliver over 1 mA to their targets and use TRIUMF-type ion sources described in this paper. Large hospitals like Vancouver General Hospital [13] (VGH) and radio pharmaceutical producers like Nordion [14,15] also use the TRIUMF build ion sources for the injection into their cyclotrons.

Beside the application as beam injector to cyclotrons H^- ions are used to provide protons to high power storage rings with multi-turn injection. An accelerated H^- beam is fed to the storage ring through a stripping foil and a magnetic dipole. The H^- beam bends into the ring in the dipole and electrons of the H^- stripped by the thin foil. The protons then accumulate in the ring, passing multiple times through the stripping foil unaffected. This allows a large number of protons to be stored in the ring (CERN and Fermilab).

In fusion research, energetic neutral beams are used for plasma generation and heating. They are created by the neutralization of negative ion beams. It is the only viable option because at energies above 100 keV the positive ion neutralization efficiency is too low to create neutral beams of the required densities. The high current version of the TRIUMF type H^- source is intended to use in fusion research.

1.1. H^- production

The most common methods to produce H^- ions are volume production via dissociative electron attachment and surface production on a thin coat of alkali metal. Only volume production is discussed here since it is robust, involves less breakdowns and has easy maintenance as well as simple operation and it is chosen for TRIUMF development.

According to the calculations by Wadehra and Bardsley [16] the highest cross section for H^- volume production is from the dissociation of a H_2 molecule in a vibrational state above $v = 4$. The most known

* Corresponding author.
E-mail address: keerthi@triumf.ca (K. Jayamanna).

https://doi.org/10.1016/j.nima.2018.03.073
Received 9 December 2017; Received in revised form 19 March 2018; Accepted 28 March 2018
Available online 11 April 2018

reactions to produce H^- ions are shown in Fig. 1 [17,18]. Cross section values for the following reactions are given where available and for optimum energies.

$H_2^*(v = 4) + e(\sim 0.5 \text{ eV}) \rightarrow H^- + H$ (dissociative electron attachment $\sigma = \sim 3.8 \cdot 10^{-17}$ cm^2).

Cross section for dissociative electron attachment from ground state molecules is about five orders of magnitude lower.

$H_2 + e(\sim 3.7 \text{ eV}) \rightarrow H^- + H^*$ (dissociative electron attachment $\sigma = \sim 1.6 \cdot 10^{-21}$ cm^2).

H^- ions can also be produced through polar dissociation with energetic electrons but the cross section is still lower than to dissociative electron attachment with exited H_2 molecule

$H_2(v = 0) + e(\sim 38 \text{ eV}) \rightarrow H^- + H^+ + e$ (polar dissociation $\sigma = \sim 1.6 \cdot 10^{-20}$ cm^2).

Therefore, the only viable option to enhance H^- ions is to increase the density of the vibrationally exited molecules at higher states. Vibrationally exited molecules are created by hydrogen gas colliding with higher energy electrons in the plasma as well as through recombination processes on volume and on wall collisions.

$H_2 + e(\geq 60 \text{ eV}) \rightarrow H_2^*(v \geq 4) + e$

$H_2^*(v) + e(\sim 1 \text{ eV}) \rightarrow H_2^*(v + 1) + e.$

Volume based cusp ion sources produces H^- mainly from volume processes therefore surface production or recombination is not described here and can be found elsewhere [19].

1.2. H^- destruction

H^- ions recombine while colliding with high energy electrons, neutral atoms, molecules, positive ions as well as plasma chamber walls

$H^- + e(\geq 15 \text{ eV}) \rightarrow H + 2e$ (collisional detachment $\sigma = 4 \cdot 10^{-15}$ cm^2)

$H^- + H_2 \rightarrow H_2 + H^* + e$ (collisional detachment $\sigma = 1 \cdot 10^{-15}$ cm^2)

$H^- + H^+ \rightarrow H_2$ (charge transfer $\sigma = 2.5 \cdot 10^{-13}$ cm^2)

$H^- + H_2^+ \rightarrow H_2 + H$ (collisional detachment)

$H^- + H_3^+ \rightarrow 2H_2$ (charge transfer)

$H^- + wall \rightarrow H + e$ (wall collision).

1.3. Background electrons

It is clear that the high energy electrons are needed to sustain plasma and for producing exited molecules while only low energy electrons should be present near the extraction region where H^- ion production must occur. Hot filament and an arc discharge are common as the electron driver and could produce energetic electrons as high as the arc energy to produce plasma and exited molecules. The fraction of low energy electrons produced in the plasma increases with the gas pressure. It is imperative to filter and stop high energy electrons entering the extraction region where H^- ions are produced and extracted. It was found that creating a simple transverse field called virtual filter can easily filter the high energy electrons while letting the low energy electrons migrate through the filter due to the difference in the Larmor radius. Higher energy electron bend away from the center due to large Larmor radius. Low energy electron with small Larmor radius move close to the center known as Bowman diffusion.

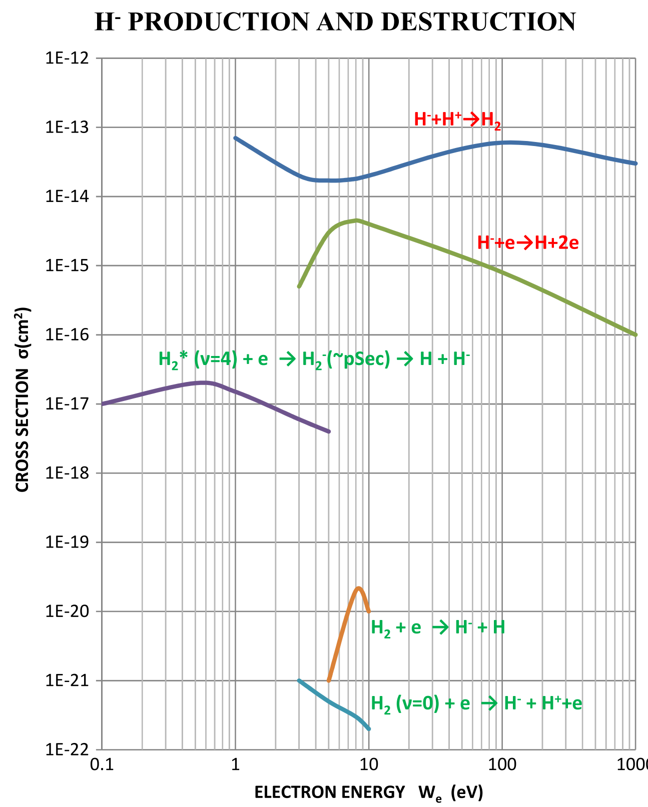

Fig. 1. The cross sections of the H^- production processes (Green) and destruction processes (Red). Only the reactions with the highest cross section for both processes are shown here for clarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Source setup

TRIUMF has been developing arc discharge H^- ion sources based on volume production [19,20] and multi-cusp magnetic configuration since the mid-eighties. In 1989, 9 mA was reached [20] and 15 mA was achieved [21] in 1995. After a long break, H^- development started again in 2012 in order to improve performance of the main H^- ion source of the TRIUMF 500 MeV cyclotron and to fulfill future requirements of the fusion research. The goal was to design a source with a brighter and higher H^- current as well as to develop a long-lasting filament. A state-of-the-art test stand was built for that purpose and 20 mA was achieved [22] soon after commissioning it in 2013. In order to allow operation at higher currents significant improvements had to be done. Those are described in the following section.

2.1. Ion source and extraction system

A schematic of the source set-up can be seen in Fig. 2a. A water-cooled, 100 mm diameter, 150 mm long and 2 mm thick beryllium copper plasma chamber reinforced with stainless steel flange and surrounded by a 10 pole, 20 row Halbach type cusp magnetic configuration (Fig. 5) serves as the plasma chamber of the ion source. Four poles are also installed and arranged in the back plate where the filament holders are located, so that the cusp confinement continues throughout the plasma volume. The arc is created by applying a voltage of up to 200 V between a hot filament and the plasma chamber.

Two extraction systems, a three electrode (accel-accel — Figs. 2a and 2b) and a four electrode (accel-accel-decel — Figs. 3 and 4), were tested. The three-electrode system is simple but optimal only for fixed energy at 30 keV for the fixed gaps between electrodes. The four-electrode