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

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A R T I C L E   I N F O

A B S T R A C T

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 CY-CIAE 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.
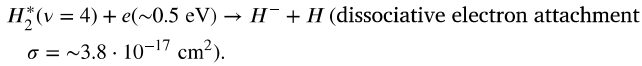
1.1. H^- production

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

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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.

$H_2^*(v = 4) + e(\sim0.5 \text{ eV}) \rightarrow H^- + H$ (dissociative electron attachment

$\quad \sigma = \sim3.8 \cdot 10^{-17} \text{ cm}^2$).

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

$H_2 + e(\sim3.7 \text{ eV}) \rightarrow H^- + H^*$ (dissociative electron attachment

$\quad \sigma = \sim1.6 \cdot 10^{-21} \text{ cm}^2$).
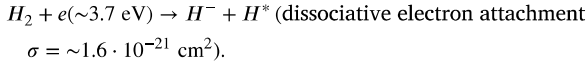
H^- ions can also be produced through polar dissociation with energetic electrons but the cross section is still lower than to dissociative electron attachment with exited H_2 molecule
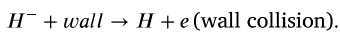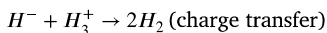
$H_2(v = 0) + e(\sim38 \text{ eV}) \rightarrow H^- + H^+ + e$ (polar dissociation

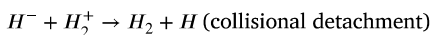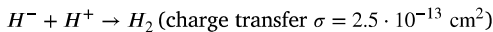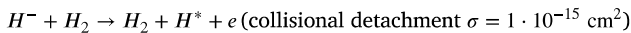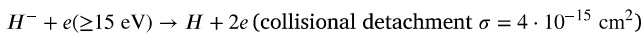$\quad \sigma = \sim1.6 \cdot 10^{-20} \text{ cm}^2$).
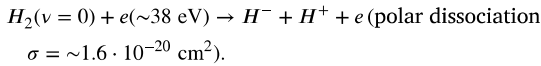
Therefore, the only viable option to enhance H^- ions is to increase the density of the vibrationally exited molecules at higher states. Vibrationally exited molecules are created by hydrogen gas colliding with higher energy electrons in the plasma as well as through recombination processes on volume and on wall collisions.

$H_2 + e(\geq60 \text{ eV}) \rightarrow H_2^*(v \geq 4) + e$

$H_2^*(v) + e(\sim1 \text{ eV}) \rightarrow H_2^*(v + 1) + e$.
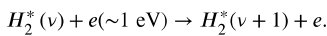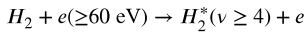
Volume based cusp ion sources produces H^- mainly from volume processes therefore surface production or recombination is not described here and can be found elsewhere [19].

1.2. H^- destruction

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

$H^- + e(\geq15 \text{ eV}) \rightarrow H + 2e$ (collisional detachment $\sigma = 4 \cdot 10^{-15} \text{ cm}^2$)

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

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

$H^- + H_2^+ \rightarrow H_2 + H$ (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.
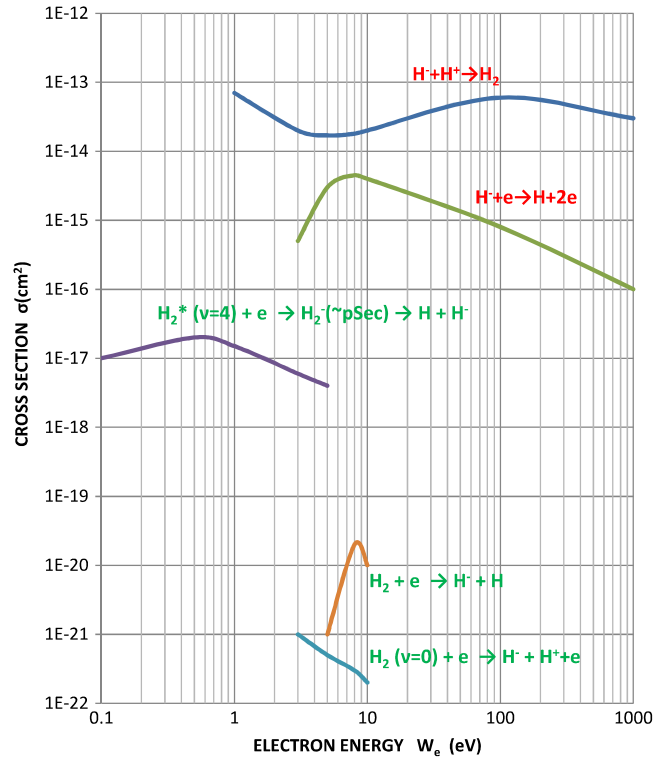

H⁻ PRODUCTION AND DESTRUCTION

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.)
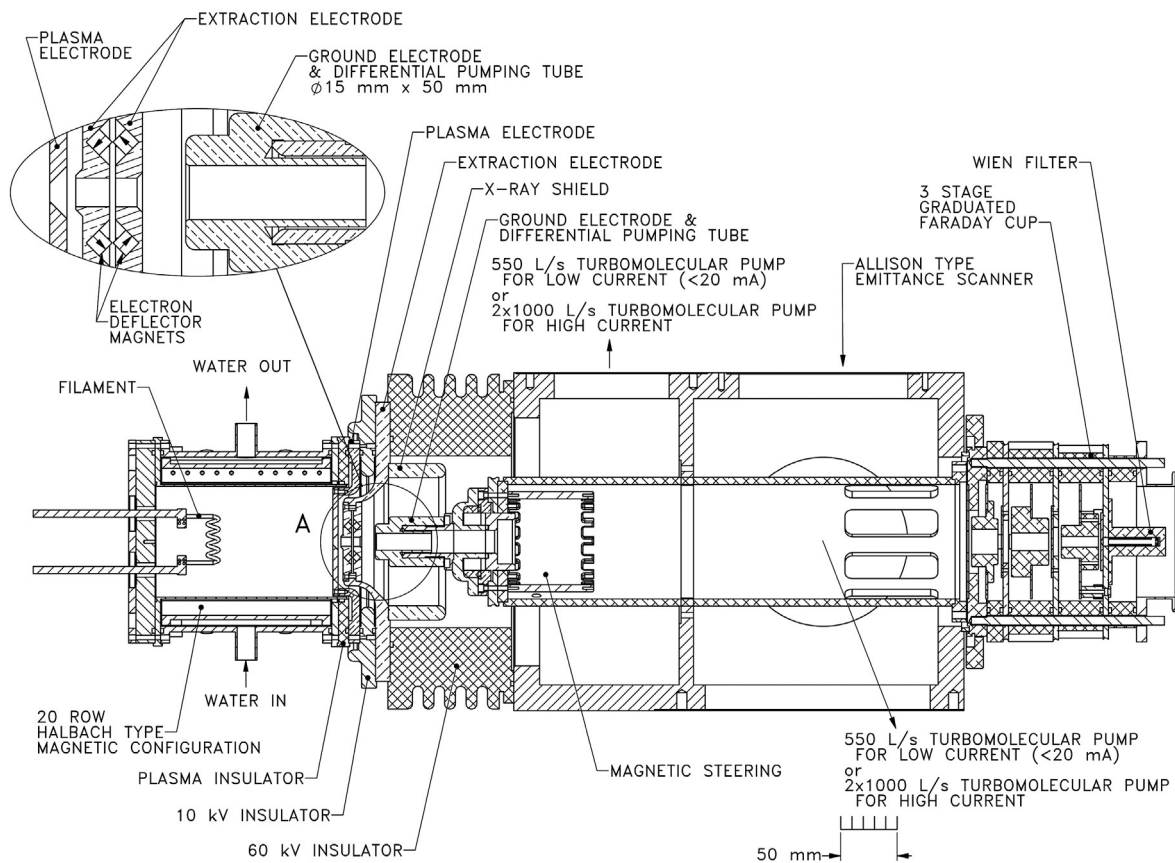
2. Source setup

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.
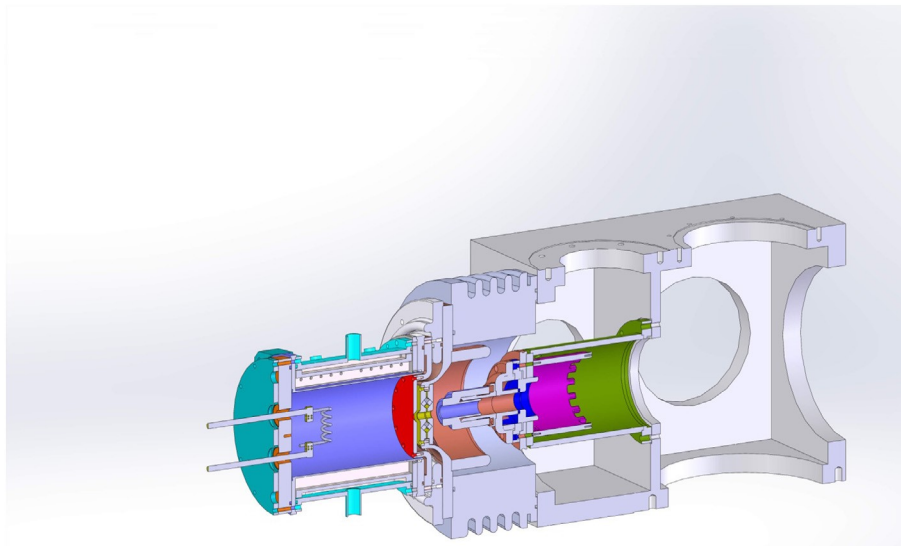
2.1. Ion source and extraction system

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

Fig. 2a. Schematic view of the source setup with 3 electrode extraction system. The distance between the plasma electrode and the extraction electrode is 2.8 mm and the distance between the extraction electrode and the ground electrode is 14 mm.


Fig. 2b. A 3D cross-section of the ion source and extraction system with three electrodes. See the adjustable differential tube at the ground electrode front nozzle end.

system allows the source to run at optimum extraction voltage for a large range of extracted beam energies with minimal impact on the beam properties [22]. With this extraction system, the beam energy can be as low as 1 keV and as high as 60 keV with negligible changes in beam quality.
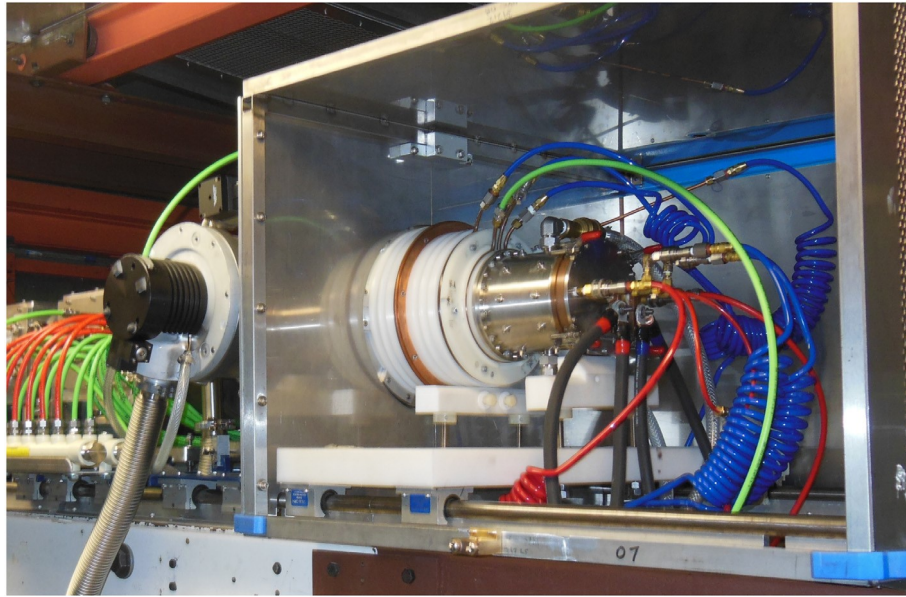
2.1.1. Electron filters

Two electron filters are necessary as described above for H^- production. By reversing 10 short magnets in the cusp at selected places (see Fig. 5) at the horizontal axis, a small dipole field (virtual filter) was created. It filters the high-energy electrons from the low-energy electrons [20]. An IV curve from a movable Langmuir probe (Fig. 6)
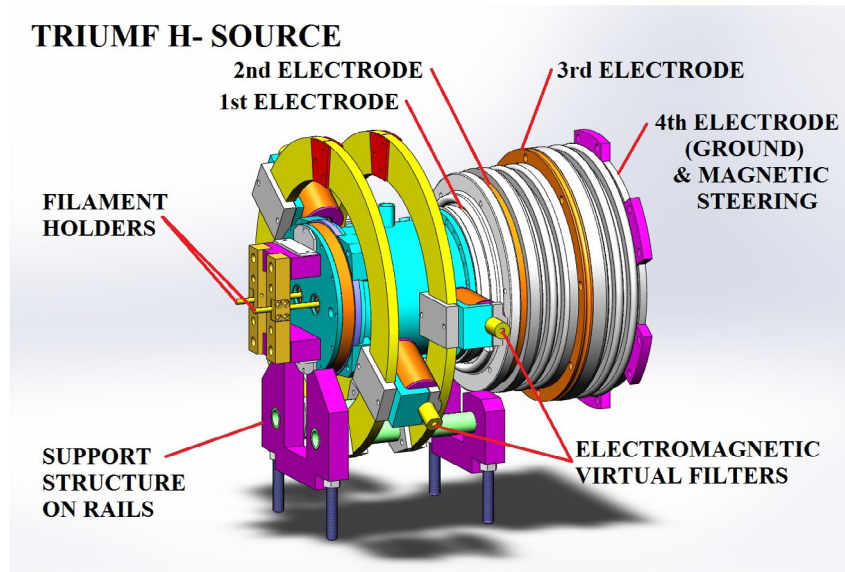
Fig. 3. A 3D view of a four-electrode extraction system (accel-accel-decel) with adjustable electromagnetic virtual filters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Ion source with four electrodes (accel-accel-decel). External coils were removed after optimizing and rearranging the virtual filter.

along the axis of the source determined the optimum values of the electron filters [23]. Measured positive ion density along the axis is shown in Fig. 7. Four electromagnetic filters are also installed (Fig. 3 Orange) in order to optimize the virtual filter created by the permanent magnets dipoles for various arc conditions [22]. After optimizing, the electromagnets were removed by reorganizing cusp permanent magnets to produce the same magnetic field. Near the extraction aperture where the majority of H^- is created, the electron temperature must be around 0.5 eV for dissociative attachment of vibrationally excited hydrogen molecules. Everywhere else, high-energy electrons are beneficial for producing as many excited hydrogen molecules as possible in order to maximize H^- production. Therefore optimization of the virtual filter is utmost important for volume production based high current H^- output.

Another two pairs of small 3 mm × 5 mm × 25 mm magnets are installed in the extraction electrode (see Fig. 2a top left) to remove any electrons extracted from the source before gaining full energy. These electrons must be removed from the beam to reduce space charge

problems as well as to reduce unnecessary power drainage from the high voltage bias power supply. The majority of the electrons return back to the plasma electrode because of the filters, but some escape and reach the extraction electrode (second electrode). Due to the strength of these magnetic dipoles no significant amount of electrons were found passing the extraction electrode along the beam path. A Wien filter shows no electrons with the H^- beams but does show negligible amounts of neutrals and negatively charged oxygen ions. Electromagnetic steering placed after the ground electrode (third electrode) corrects the H^- trajectory while removing any leftover electrons in the H^- beam. Fig. 8 shows the sum of transverse magnetic fields along the axis from three filters. For very high-current operation, around 2 millitesla transverse magnetic field along the beam line after the extraction system is needed to improve H^- beam transmission. This magnetic field is created by placing permanent magnets along the beam path outside the vacuum cambers.
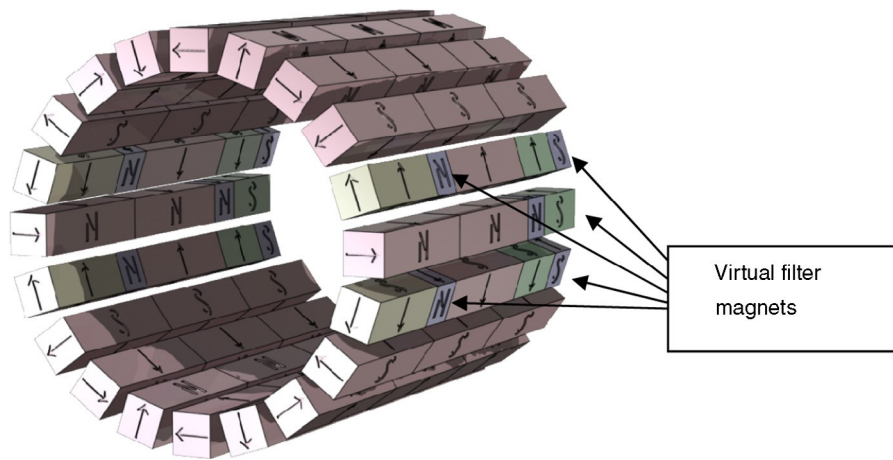
Fig. 5. Halbach magnetic configuration used in most of TRIUMF type H^- ion sources, including the test stand and the main ion source at the 500 MeV cyclotron.
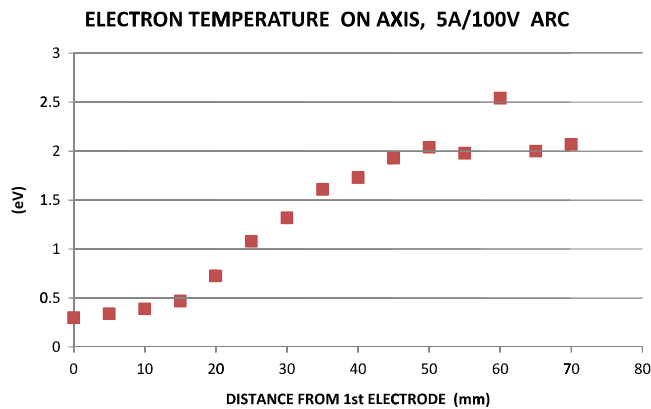

Fig. 6. Shows the electron temperature measured with a Langmuir probe on axis with 5 A 100 V arc. An aberration near the 60 mm is due to the filament interference to the probe measurements.
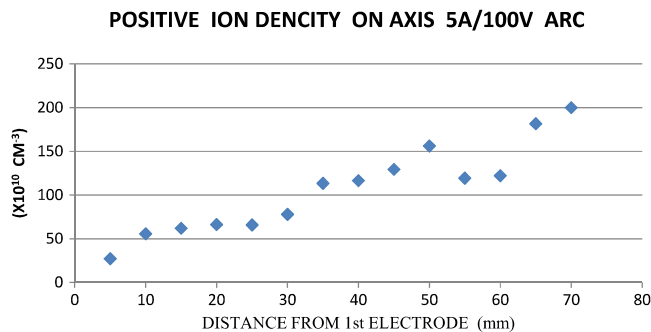

Fig. 7. Shows the positive ion density on axis measured with a Langmuir probe at 5 A 100 V arc. Above aberration near the 60 mm is also due to the filament interference to the probe measurements.
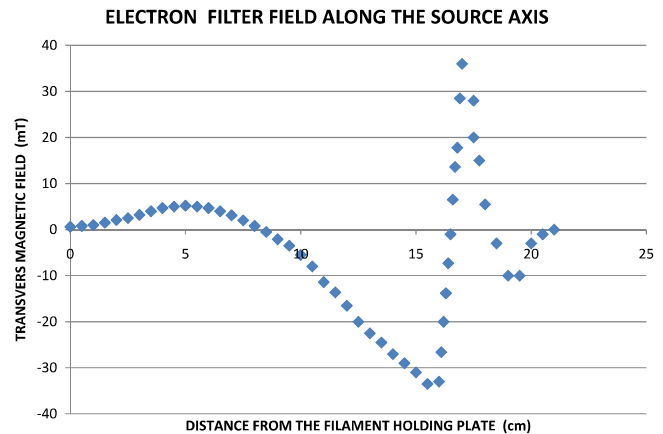

Fig. 8. Filaments are located at the 5 cm position and the plasma electrode is at the 16 cm mark. Most electrons return to the plasma electrode and the erosion is visible at the back of the plasma electrode after a long run. Any electrons that escaped from the plasma electrode will accelerate and curve into the second electrode.

2.1.2. Electrical system

The test setup is designed to operate the source high voltage terminal at a potential of up to −60 kV. An electrical schematic is shown in Fig. 9. AC power to supply a 10 V, 1000 A filament power supply and a 100 A, 150 V arc power supply and other necessary power supplies for the extraction potentials is fed in via a 45 kV. A transformer with 75 kV isolation. A −60 kV, 50 mA power supply is used to study higher extraction voltages and a −20 kV, 500 mA is used to study higher H^- currents at voltages below 20 kV. We use two high voltage power

supplies because of availability and the power constraints of the system. For the extraction electrode, a 10 kV, 400 mA power supply is installed. Another 100 kV, 1 kV. A transformer is utilized to supply uninterrupted power to controls and the safety devices. Each electrode and power supply is connected via protective circuits with varistors (GEMOVs), capacitors, ferrite toroid coils and bleeding resistors.

2.1.3. Beam line and diagnostics

A set of steerers is used to steer and center the beam to the three stage graduated Faraday cup. Two Allison type emittance scanners [24] for vertical and horizontal directions are installed in the beam line to complete the test stand.

2.1.4. Vacuum system

The vacuum system consists of four 1000 L/s (for hydrogen) turbo molecular pumps, two for the source box and two for the diagnostic box. A low current (H^- < 20 mA) version needs only two 550 L/s turbo molecular pumps, one for the source box and one for the diagnostic box. Two 600 L/min dry pumps back each section of the beam line. A 15 mm diameter and 50 mm long tube is installed between the source box and the diagnostic box in order to achieve the required differential pumping, (see Fig. 1). The differential pumping is necessary for transporting the
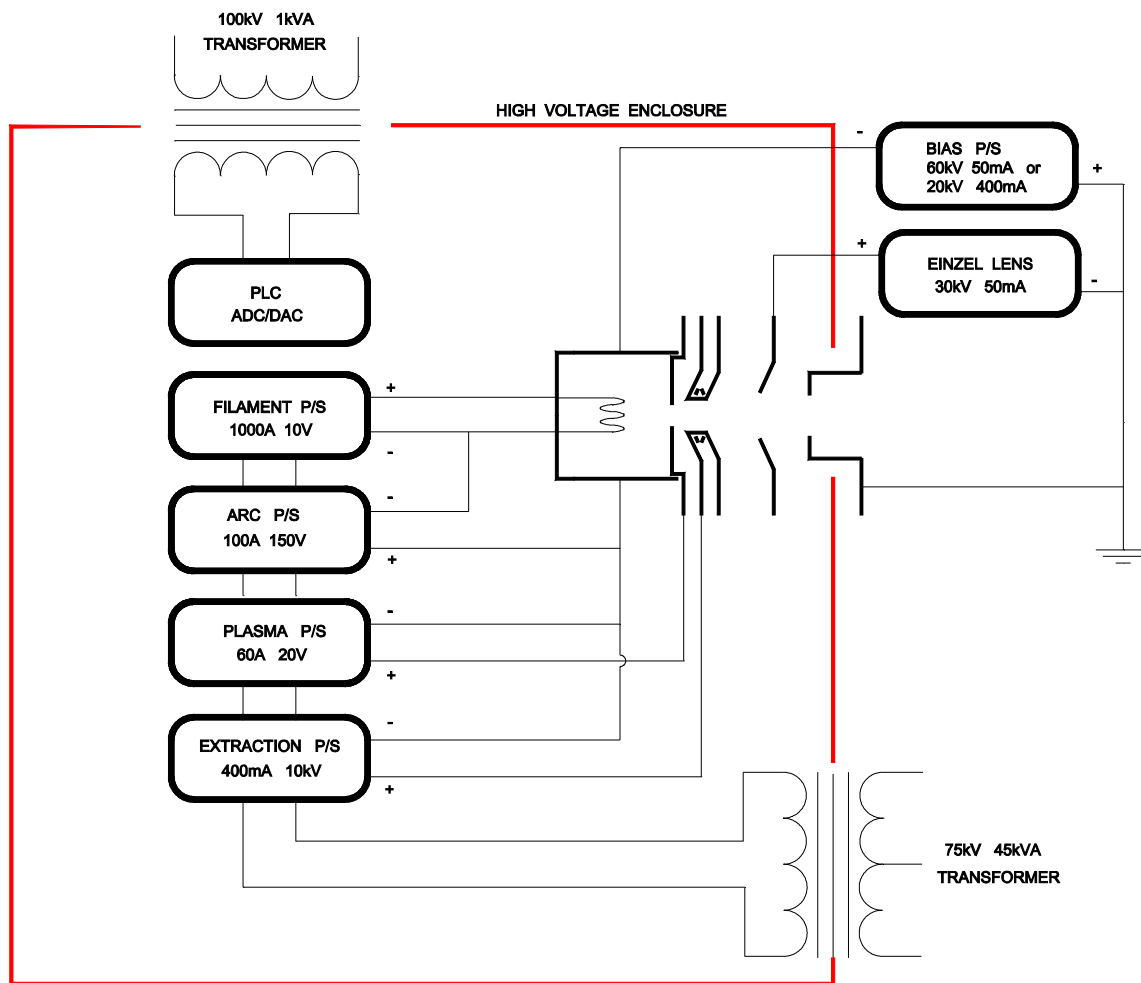
Fig. 9. Electrical schematics of the H^- ion source system with an Einzel lens as the third electrode. For fixed beam energy studies this electrode was removed and only a three-electrode system was used. Toroid rings, varistors and capacitors were installed for protection where necessary. Bleeding resistors are also installed to minimize damage to the equipment in case of sparking occurring during the vigorous testing.
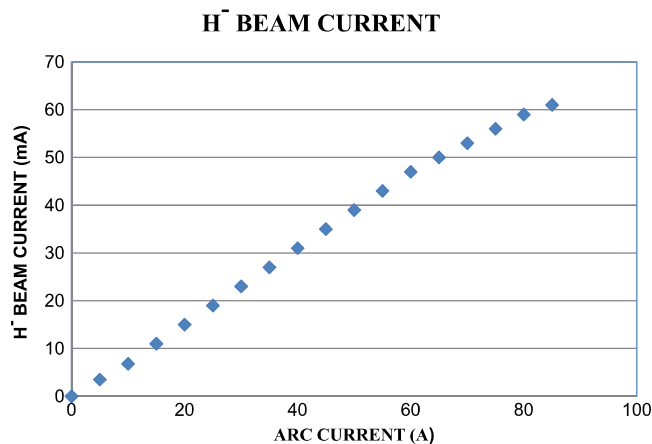

Fig. 10. Total H^- beam current at the graduated Faraday cup.

H^- beam with minimum stripping losses. Optimum H^- production at the source is ~0.4 Pa therefore removing gas as early as possible from the beam path is essential for efficient beam transmission. Optimum background pressure must be maintained in order to maximize space charge neutralization and minimize beam stripping.

Two gas flow controllers with flow rates of 0.1–10 cm^3/min STP and 3–100 cm^3/min STP are utilized for low and high current studies. Two controllers are used because the higher capacity flow controller does not have enough resolution for fine-tuning when the gas flow is below 3 cm^3/min. Also for very low H^- current with brighter beam studies, a smaller plasma aperture and a very low hydrogen flow is needed. For highest current operation (60 mA) a 66 cc/min hydrogen flow is needed.

3. Results & discussions

3.1. H^- beam current and emittance studies

The results up to 20 mA were published previously [21]. This paper describes the modifications needed to be done for the source and extraction system for higher current production and a summary of newly developed filament studies. While increasing the H^- output current, many components needed to be upgraded or modified. A 50 A, 200 V arc power supply was replaced with 100 A, 150 V unit. A 50 mA, 60 kV bias power supply was replaced with a 500 mA, 20 kV unit. An extractor power supply was also replaced with a 400 mA, 10 kV unit. A 20 row Halbach type cusp configuration with the virtual filter also went through several iterations in order to be optimized to the desired output requirement. The gaps of the extraction system also went through a few iterations.

H^- beam current was studied with respect to various other parameters. Fig. 10 shows the H^- beam current versus arc current. While
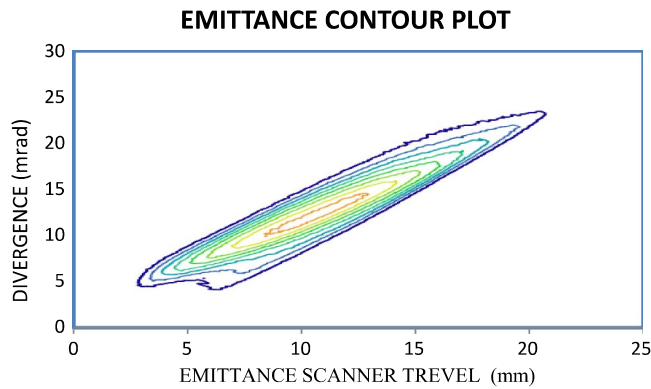
EMITTANCE CONTOUR PLOT

Fig. 11. An emittance measurement of a 60 mA H^- beam at 20 kV.

FILAMENT DECAY STUDIES

Fig. 12. Four different filaments were developed for different arc currents and characterized. TRF200-20 a single filament is suitable for up to 20 A arc and the filament usable current range is 200 A. Filament lifetime can be estimated by usable filament current divided by filament decay at required arc current. It is clear that the larger the filament, the longer the filament life but compromise must be made depending on the power available for the filament at the source high voltage terminal.

these measurements were taken, all other parameters including hydrogen flow, plasma electrode voltage and extraction electrode voltage were adjusted to both maintain manageable electron currents on the extraction electrode and maximize the output. Arc power became a significant source of filament heating therefore arc current stabilizing proportional integral derivative (PID) loop parameters needed to be adjusted accordingly. Emittance of the 90% beam at 60 mA was found to be 78π mm mrad. (See Fig. 11).

3.2. Filament life time studies

Tantalum and tungsten filaments (1 mm to 4 mm diameter) with various lengths and shapes were studied. Tantalum filaments produced H^- beams that were both brighter and of higher current but degraded faster than tungsten based filament at higher arc currents. Detailed
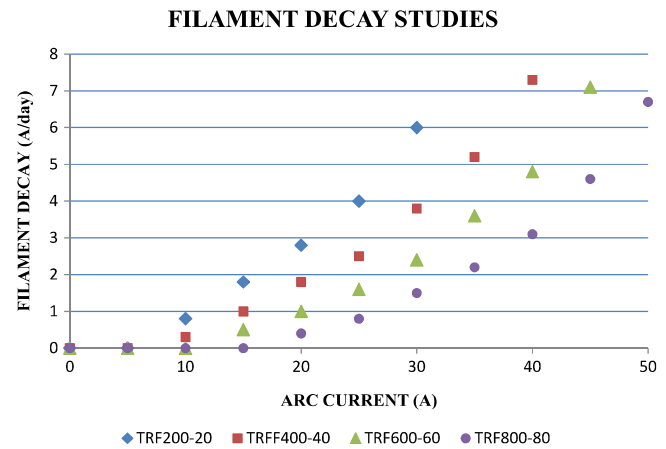
discussion regarding filament shapes, sizes as well as its composition are beyond this paper's scope.

Since the filament lifetime is measured in months, it is difficult to measure each filament precisely. The lifetime of the filament can be estimated by the decrease in heater current while keeping a constant arc current using software (PID) loop. It is presented as amperes per day with the usable filament current range (see Fig. 12). From these numbers, the filament lifetime can be extrapolated with reasonable

Fig. 13. Cathode (TRF800-80) capable of producing 60 mA of H^- with 90 A at 140 V arc is made of four 2.5 mm diameter Tungsten filaments. Note the cone loss cusp lines from each filament on the back plate.

FILAMENT LIFETIME COMPARISON
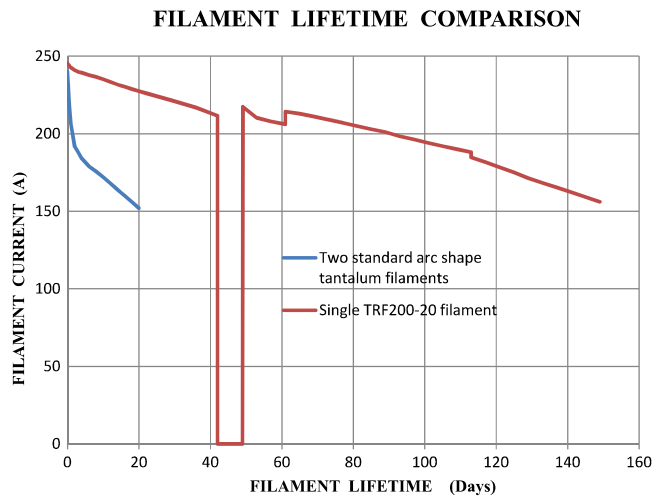
Fig. 14. Superimposed filament decay data from the TRIUMF 500 MeV cyclotron ion source. The blue line indicates the standard two of 2 mm diameter arc shaped filaments. The red indicates the newly developed single tungsten filament of 2.5 mm diameter. In both cases the arc current and arc voltage are 7 A and 100 V respectively and the extracted H^- current was 1.2 mA at 12 kV with 5 mm aperture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

accuracy. The filament used for highest H^- current (60 mA) is shown in Fig. 13. In this case, over 800 A of filament current is needed to initiate plasma but at 90 A and 140 V only 400 A is needed to heat the filament due to an additional filament heating by the arc power.

In order to produce 20 mA of H^- with a 14 mm plasma aperture a single filament (blue in Fig. 12 — TRF200-20) is sufficient. Up to 5 A of arc current none of the filaments showed any measurable decay while the largest filament (4 of 2.5 mm tungsten based) did not show any measurable decay when tested with up to 15 A arc current. The results specially filament lifetime achieved can be applied to medical cyclotrons as well as other H^- machines with filament based ion sources and reduce maintenance time significantly.

The smallest filament tested is now installed in the TRIUMF 500 MeV cyclotron and has been running for over 6 months with 7 A arc current and 100 V arc. This is the first time in the cyclotron's history that the filament could last from shutdown to next shut down without replacing it. Filament decay of the main cyclotron H^- ion source is shown in Fig. 14. Note the beam off time in the plot is for cyclotron mini shutdown activity related work and not related to the source.

The same filament was installed in the TR13 cyclotron and running nearly a year at 4 A and 100 V arc without seen any noticeable filament degradation.

4. Conclusion

With the installation of a new high power cathode and optimizing the virtual filter in the H^- ion source, output current has been increased to over 60 mA DC beam at 90 A and 140 V arc. The emittance$_{90\%}$ was measured to be 78 π mm mrad for the highest current extracted. Four different filament configurations were tested for four different arc current ranges and their lifetimes are presented. The new filament design allows operation of the main H^- ion source at the 500 MeV cyclotron for more than 6 months at 7 A arc current, compared to 3 weeks with the old design. The same filament was installed in TR13 cyclotron dedicated for short-lived radioactive isotope production for hospitals is running more than a year without noticeable degradation. Higher power version with four filament is intended to use in fusion research and can run continuously up to four weeks until the next filament change. The results will benefit machines with filament based H^- ion sources including medical cyclotrons and fusion research machines.

Acknowledgment

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