# High brightness H− ion source for accelerators developed at TRIUMF

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**6 authors**, including:

K. Jayamanna
TRIUMF


Friedhelm Ames
TRIUMF


Gabriel Cojocaru
TRIUMF

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K. Jayamanna, F. Ames, Y. Bylenskii, et al.

# High Brightness H- Ion Source for Accelerators Developed at TRIUMF

K. Jayamanna [a)], F. Ames, Y. Bylenskii, G. Cojocaru, B. Minato and M. Lovera

*TRIUMF, 4004 Wesbrook Mall, Vancouver BC, Canada V6T2A3*

[a)]Corresponding author: keerthi@triumf.ca

**Abstract.** TRIUMF has developed H- ion sources for decades and now they are being employed in TRIUMF cyclotrons as well as in various other machines. A high current version can produce up to 60 mA [1]. A medium range source is optimized to produce 20 mA. A new smaller H- ion source with a plasma volume of 50 mm x 75 mm ion source is being developed to produce 5 mA at a very low emittance and run years without changing the filament. Due to the low emittance and relatively little required maintenance, this ion source will suit cyclotrons as well as accelerators looking for reliable, stable operation with very low maintenance. Having four electrodes, this ion source can run at optimum extraction voltage while delivering the beam from 1 kV to 60 kV with little or no degradation of the beam quality. Performance of the source including beam current, arc parameters, emittance and filament lifetime are discussed in this paper.

## INTRODUCTION

The 500 MeV cyclotron and other small cyclotrons including TR13 and TR 24 at TRIUMF employ arc discharge ion sources developed decades ago. They are currently being utilized in cyclotrons developed by manufacturers like ACSI, BEST, and CYCIAE. Large hospitals like Vancouver General Hospital (VGH) and radiopharmaceutical producers like BWXT also use the TRIUMF-built ion sources for the injection into their cyclotrons. They run continuously, providing beams for experiments and producing valuable radioactive isotopes for research and medical purposes [2, 3]. The only interruption to these machines is to replace the worn filament or to clean the plasma cavity at regular intervals. Replacing filaments is a major factor of a cyclotron operation's downtime and valuable time is lost in replacing the filament and removing the debris and flakes left by the worn filament material. Long life filaments will reduce the frequency of maintenance and minimize flakes in the source, therefore improving the reliability and the stability of the beam and the machine. Improved beam quality could increase cyclotron transmission leading to less radiation activation and safer maintenance. Also, it would reduce radiation damage to items near the machine which are difficult to replace by human intervention due to higher radiation activity. Our objective is to design a new simple ion source with improved beam quality and increased filament lifetime for all of the TRIUMF H- ion source terminals, which will eventually benefit all the machines employing external ion sources.

## BACKGROUND

### $H^-$ Production

The most common methods to produce H- ions are volume production via dissociative electron attachment [4] and surface production on a thin coat of alkali metal [5]. Only volume production is discussed here since it is robust, involves fewer breakdowns and is easier to maintain and operate and therefore it is chosen for TRIUMF for all the cyclotrons except CP42, which has an internal ion source. According to the calculations by Wadehra and Bardsley [6], the highest cross section for H- volume production is from the dissociation of a $H_2$ molecule in a vibrational state

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above ν = 4. The most known reactions to produce H- ions are shown in Fig. 2. Cross section values for the following reactions are given for optimum energies and where available.

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

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

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

H- ions can also be produced through polar dissociation with energetic electrons, but the cross section is still lower than the dissociative electron attachment with excited $H_2$ molecule.

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

Therefore, the only viable option to enhance H- ions is to increase the density of the vibrationally excited 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.

$$H_2 + e\ (\geq 60 eV) \rightarrow H_2^* \ (\nu \geq 4) + e$$

$$H_2^* \ (\nu) + e(\sim 1 eV) \rightarrow H_2^* \ (\nu + 1) + e$$

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

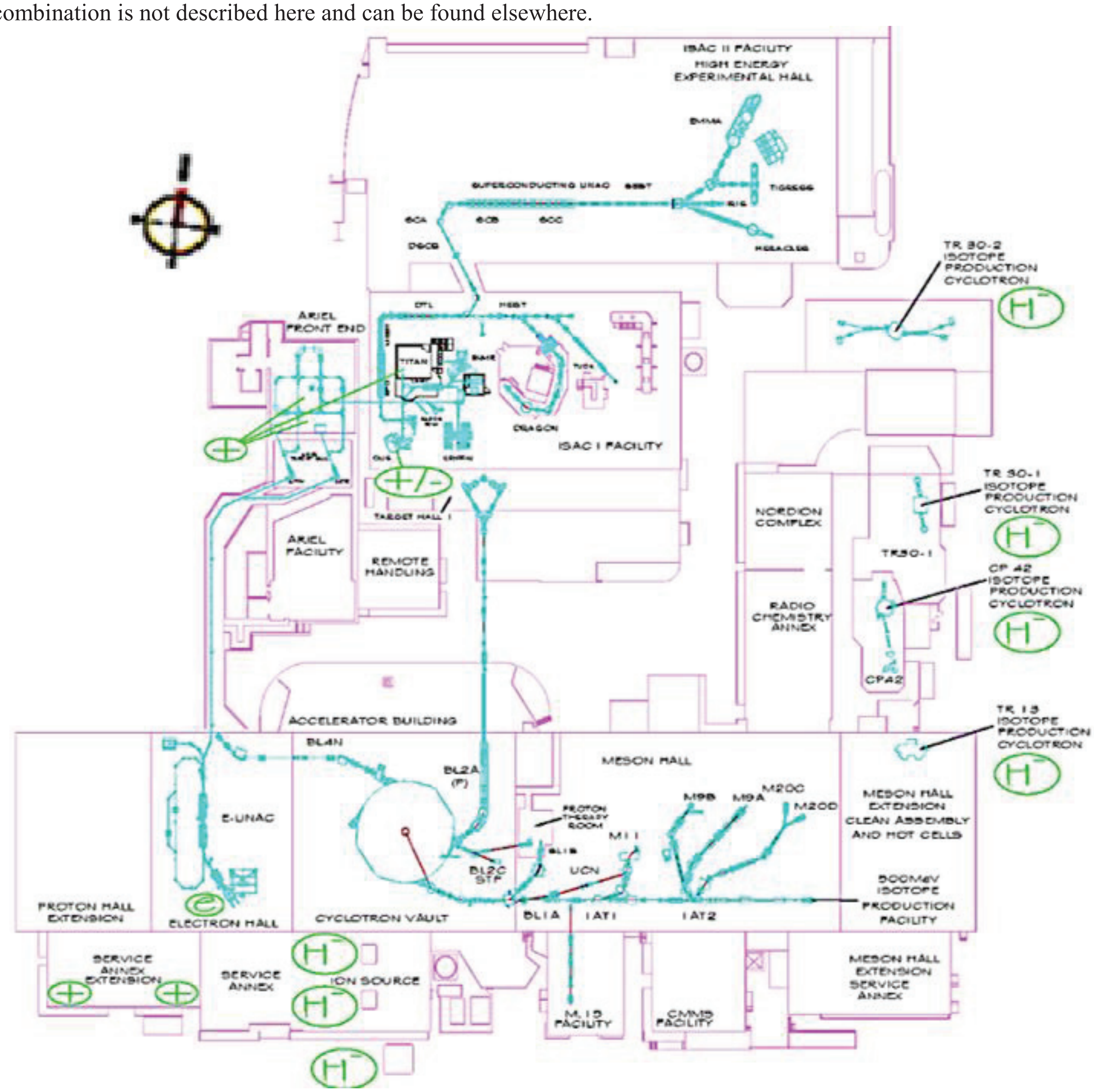



**FIGURE 1.** H- Ion source terminals at TRIUMF

## H- Destruction

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

$H^- + \; e\,(\geq 15\text{eV}) \rightarrow H + 2e$ (collisional detachment σ = 4·10^-15 cm^2)
$H^- + H_2 \rightarrow H_2 + H^* + e$ (collisional detachment σ = 1·10^-15 cm^2)
$H^- + H^+ \rightarrow H_2$ (charge transfer σ = 2.5·10^-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)

## H- Ion Production Optimization

Both high and low energy electrons are essential for H- production. The high energy electrons are needed to sustain plasma and for producing excited molecules while only low energy electrons should be present near the extraction region where H- ion production must occur. Arc discharge is the most used as the electron driver and could produce energetic electrons as high as the arc energy to produce plasma, which is responsible for producing excited molecules. The probability of low energy electrons and excited molecules produced in the plasma increases with the gas pressure. Excited hydrogen molecules migrate unhindered by the magnetic or any electric fields. The single most important characteristic of the source is the ability to filter and stop high energy electrons from entering the extraction region

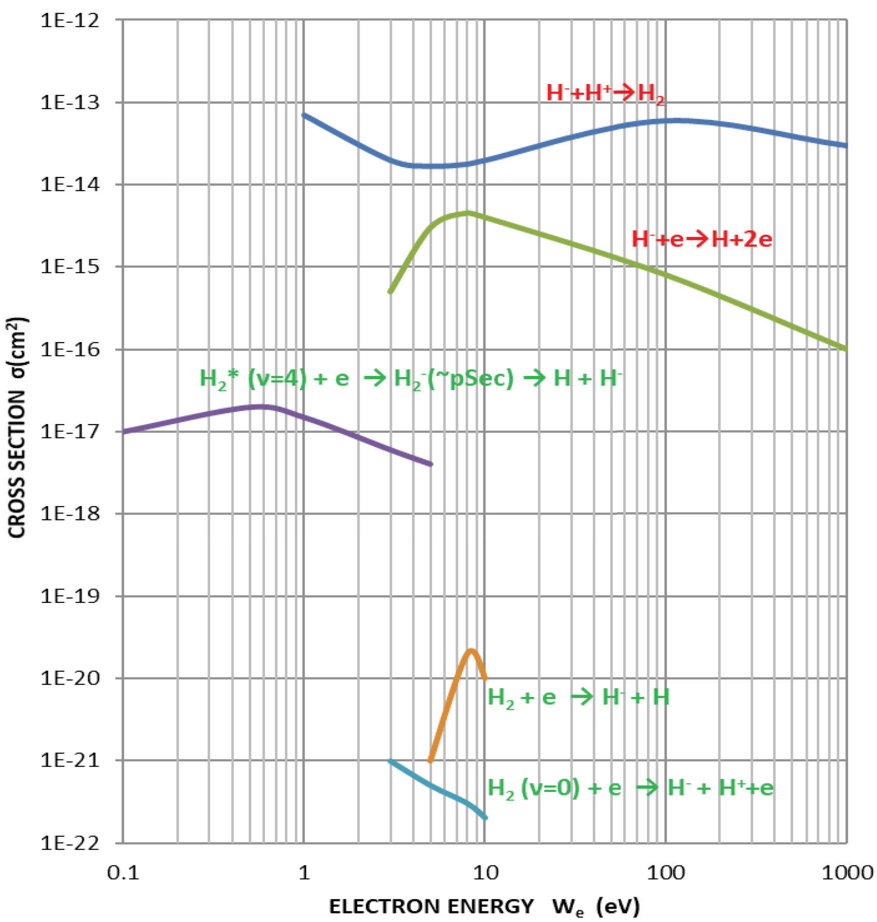



**FIGURE 2.** The cross sections of the H- production processes (Green) and destruction processes (Red). Only the reactions with the highest cross section for both processes are shown here for clarity.

where H- ions are produced and extracted while letting low energy electrons, less than 1 eV, pass through to the extraction region. It was known that creating a transverse sig-sad type field called virtual magnetic filter can easily separate the high energy electrons while letting the low energy electrons migrate through the filter due to the difference in the Larmor radius. Higher energy electrons bend away from the center due to large Larmor radius. Low energy electrons with smaller Larmor radii move close to the source axis, which is known as Bowman diffusion.

## SOURCE SETUP

The new mini cusp source consists of a smaller plasma chamber, surrounded by a magnetic confinement imbedded with a virtual magnetic filter designed to minimize H- beam emittance. There are two extraction systems designed for this source. One consists of three electrodes: the plasma electrode, the extraction electrode and the ground electrode. Another consists of four electrodes and will be used when variable energy is required. The extra electrode is added in between the extraction electrode and the ground electrode and acts as an Einzel lens therefore source can always run at its optimum voltage while delivering beams as low as 1 kV and up to 60 kV with minimum change in emittance. A new electron filter was also designed specifically for this ion source to achieve the lowest emittance possible.

The high voltage terminal is equipped with filament, arc, first electrode and extraction power supplies as well as controls and design to elevate up to 75 kV. Two separate transformers provide two separate ground circuits, one for controls as well as for safety devices and another for high current and high voltage circuits for stable and reliable operation. Even though the high voltage terminal is equipped to run high power ion sources, the ion source described in this paper utilizes only a fraction of the total power.

The beam line consists of two emittance scanners [7], a permanent magnet focusing solenoid [8], a graduated Faraday cup and the necessary steering elements. The vacuum system is equipped with four turbo pumps backed by two dry pumps and ion gauges.

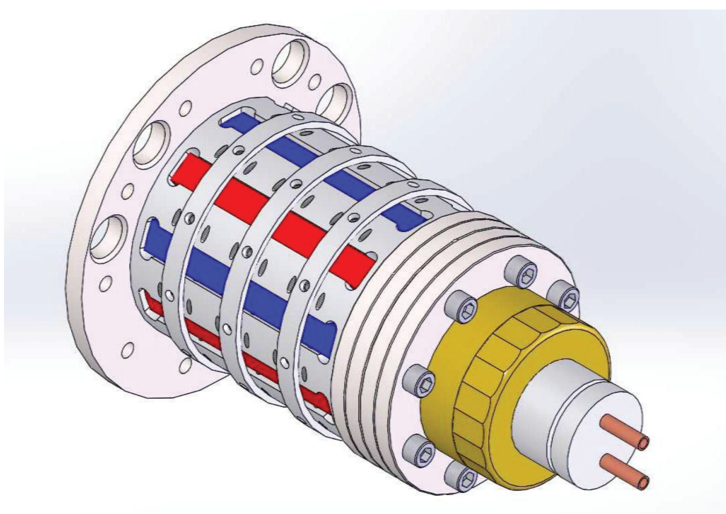
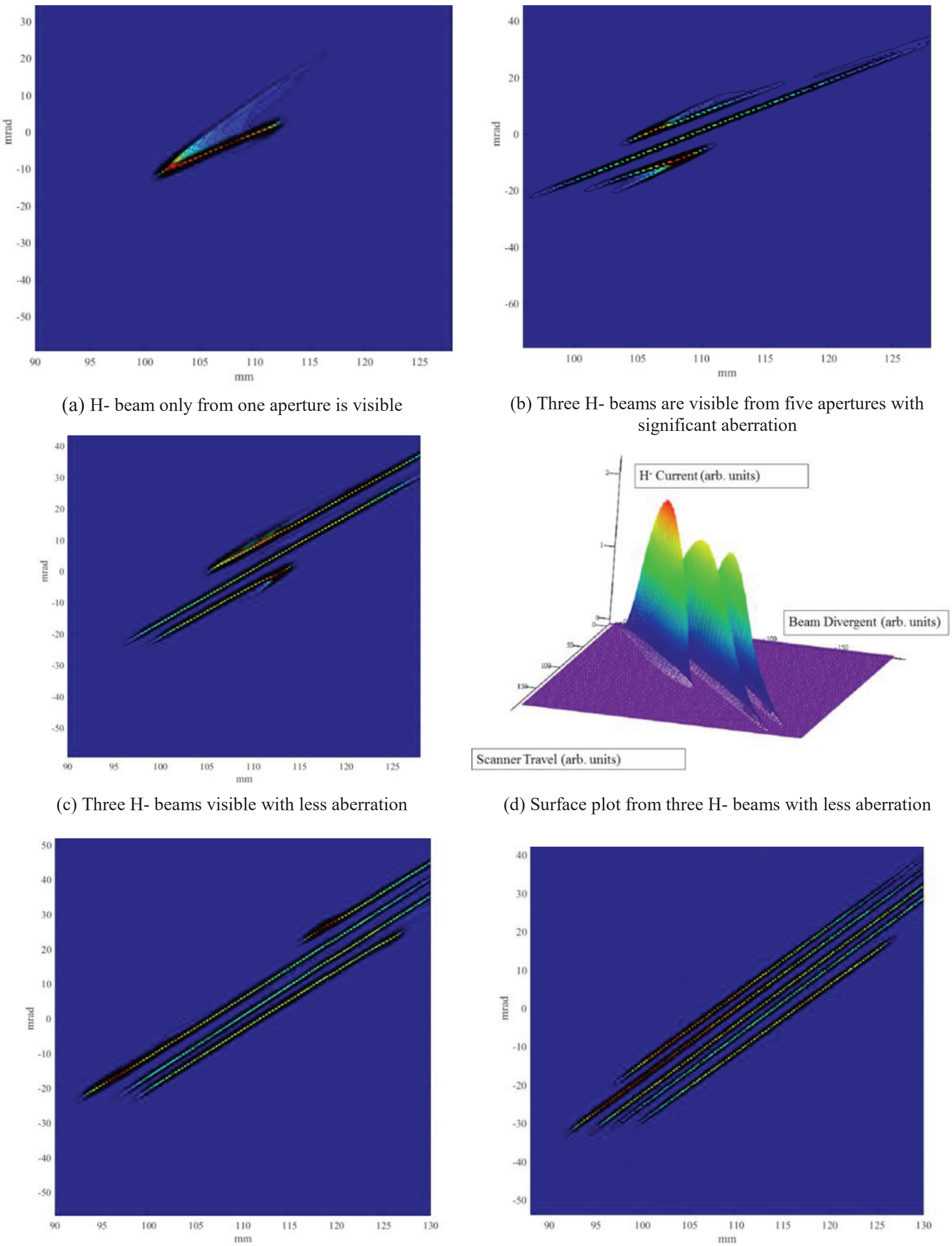


**FIGURE 3.** SolidWorks model of the TRIUMF mini H- ion source.

## RESULTS

### Extraction System Optimization

The extraction systems simulation for positive ions with or without uniform magnetic fields is straightforward and the results are accurate and agree with the experiments. However, H- extraction simulation is complicated by the nonlinear magnetic field created by the electron filter and the asymmetric space charge effects influence by electrons exiting the beam path due to the magnetic field created by these pair of magnetic dipoles. Optimizing these dipoles is important to brighter beams to minimize losses in the beam path. High gas pressure, optimum to H- production near the extraction vicinity also aggravate the problem further.




(a) H- beam only from one aperture is visible

(b) Three H- beams are visible from five apertures with significant aberration

(c) Three H- beams visible with less aberration

(d) Surface plot from three H- beams with less aberration

(e) H- beam from 4 apertures visible with less aberration

(f) H- beam from all apertures visible with less aberration.

**FIGURE 4.** Five multaperture method was used to study and optimize the extraction system

Five small apertures align with the same direction as the emittance scanner and were used to study the extracted beam. Fig. 4 (a) shows the first iteration of the test and beam is only visible from a single aperture. After a few adjustments, beams from three apertures appeared with some aberration (see Fig. 4(b)). Figure 4(c) show three beams with less aberration. Surface plot of the three beams with less aberration is shown in Fig. 4(d). In Fig. 4(e) four out of five beams were seen. After many adjustments and many iterations all five beams from five apertures were visible to the emittance scanner with almost no aberration, this is shown in Fig. 4(f).

The multi apertures were then removed and single aperture was installed, the diameter calculated extrapolating multi aperture statistics to obtain the desired emittance. The arc current can be adjusted to achieve the required beam current. Figure 8(a) and 8(b) show the emittance of 1 mA with 4 mm aperture and 8A/100V arc. For this arc current and arc voltage, the new filament should last for more than two years.

## Current and Emittance Measurements

H- beam current was studied with respect to a variety of other parameters. While these measurements were taken, all other parameters including hydrogen flow, plasma electrode voltage and extraction electrode voltage were adjusted according to the extraction system study values reported in the previous paragraph. Since improved new long-life filament used for this source, no PID loop was needed to engage this source. Figure 5 shows the H- beam current versus arc current for different types of apertures. Figure 6 shows the emittance behavior with the beam energy. The lowest emittance values achieved thus far is shown in Fig. 7(a) and 7(b) at 25 kV. It should mention, that after the extraction system optimization it is a pleasure to work with the source.

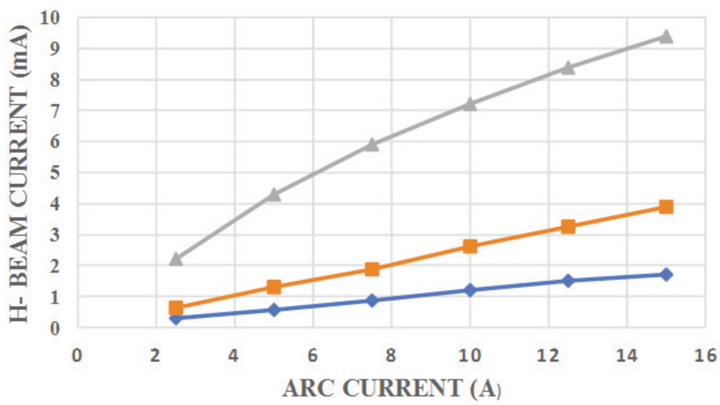



**FIGURE 5**. H- beam current versus arc current with 4 mm, 6 mm and 14 mm plasma apertures.

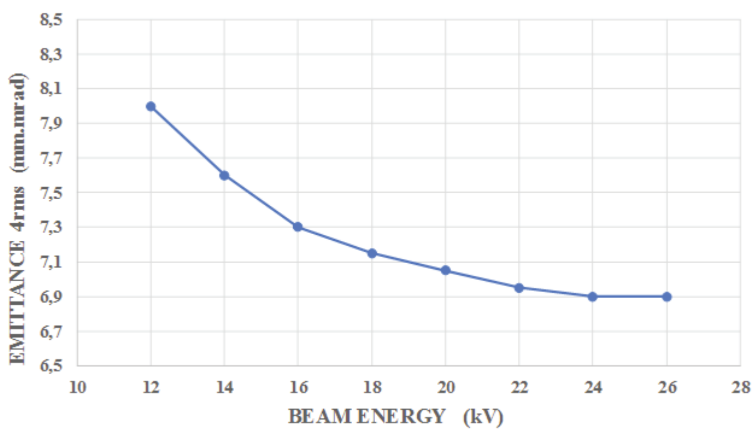
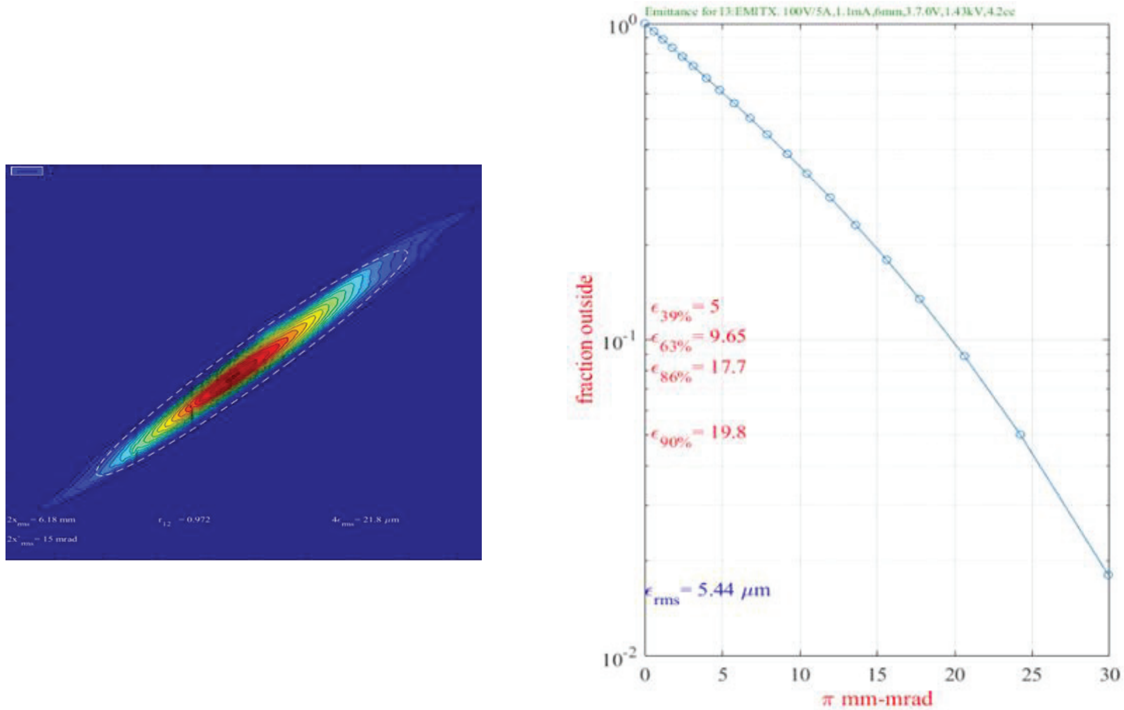



**FIGURE 6**. 4 rms emittance versus H- beam energy with three-electrode system. With the four-electrode system emittance value did not change during the same energy range.




(a) (b)

**FIGURE 7.** Emittance plot (a) and emittance value (b) with 6 mm diameter single aperture at 25 kV.

## Permanent Magnet Solenoid Studies

A 10 kg permanent magnet lens was designed to replace the 200 kg copper coil solenoid which consumed 7 kW of power continuously [8]. Copper coil solenoid capital cost was over CDN $30k including the power supply and the controls, as well as CDN $8k for yearly electricity. The permanent magnet solenoid costs only CDN $2k to build, with no electricity bill to pay. Comparison of two solenoids is shown in Fig. 8. Emittance plots and the parameters before and after the permanent magnet solenoid are shown in Fig. 9(a) and 9(b) and found to be negligible emittance increase.

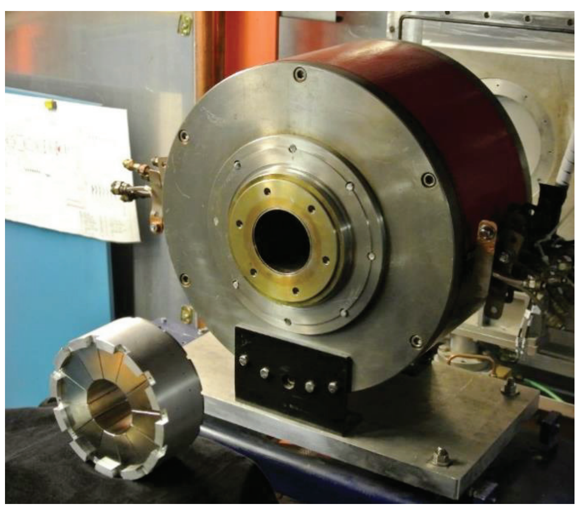
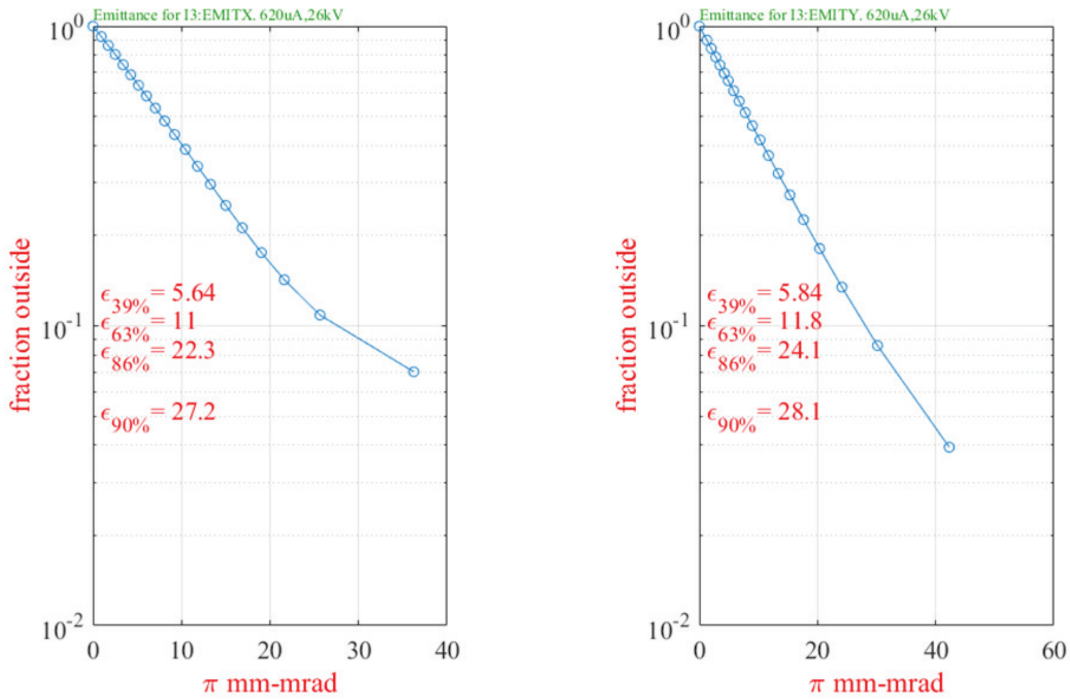


**FIGURE 8**. Compression of a single ring 12 sectored permanent magnet lens to a copper coil lens with the similar focal power.




(a) (b)

**FIGURE 9**. Emittance values of the H- beam before entering the magnet (a) and after the focusing magnet (b). Emittance and the divergence of the source needed to be increased in order to see the difference.

## CONCLUSION

A new mini H- source is developed and it is capable of delivering 1 mA H- beam with an emittance(rms) of 5.44 pi.mm.mrad at 25 kV and 6 mm plasma aperture. It also can produce an emittance (rms) of 1.7 pi.mm.mrad at 25kV and 4 mm aperture. A new virtual filter is developed for it with a matching electron dipole filter. The extraction system was optimized using the five-aperture method. A new permanent magnet focusing solenoid designed for 25 kV and was tested successfully with the source. Previously reported long-life filament is also implemented in the new source and it is now capable of running more than two years without interruptions.

## ACKNOWLEDGMENTS

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