TRIUMF H-/D- Ion Source Development to Date

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Abstract. The TRIUMF Stable Ion Source group has been developing negative and positive ion sources for decades, including a few arc-discharge H-/D- ion sources and a microwave-driven H-/D- ion source for medical cyclotrons and other applications [1]. The smallest ion source with a 125cc plasma chamber can produce up to 5mA continuously. The largest ion source with a 1200cc plasma chamber is able to produce 60mA with increased arc power, and enhanced magnetic confinement. The filament-less microwave ion source is capable of producing up to 5mA H- current for years without any manual intervention. A historical overview of H-/D- source development at TRIUMF is presented. A summary of employed optical and diagnostics components is also presented

1. INTRODUCTION

The H- ion sources developed in-house were installed on the 500MeV, TR13, TR24 and TR30 cyclotrons at TRIUMF. (figure 1). They are also currently being utilized in cyclotrons developed by manufacturers like ACSI, BEST, IBA, and CYCIAE. Large hospitals like Vancouver General Hospital (VGH) [2] and radiopharmaceutical producers like BWXT [3, 4] also use TRIUMF-developed ion sources for injection into their cyclotrons. They run continuously, providing beams for experiments and also producing valuable radioactive isotopes [5-8] for research and medical purposes. The major 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 with respect to cyclotron operation downtime and valuable time is lost in both replacing the filament and removing debris and flakes left by the worn filament material. At TRIUMF a long-lived filament has been developed to reduce the maintenance frequency and minimize flakes in the source. Magnetic confinement has also been changed with neodymium ferrous N52 and N55 magnets which has led to improved reliability and stability of the beam and the machine. Improved beam brightness has increased the cyclotron transmission, leading to less radiation activation and safer maintenance. This also reduces 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 simple series of ion sources with improved beam quality and increased filament lifetime for all of the TRIUMF H- ion sources [9, 10], which will eventually benefit machines around the world employing external ion sources. Following is the list of ion sources developed and tested to date.

2. A 125cc MINI-CUSP H-/D- ION SOURCE

The mini-cusp ion source is the smallest negative ion source developed at TRIUMF. It has a plasma volume of 125cc and weighs less than 1.5kg, including the magnets (figure 2). It also has a screw-in type easily-replicable filament holder. The magnetic structure consists of 16 rows of Halbach array type magnetic cusp confinement with an optimized virtual filter. Its small size, simplicity and the low cost make it one of the best candidates for small medical cyclotrons requiring less than 5mA of H- current. Due to its small size, cooling water flow is limited; therefore, the maximum arc power is limited to 2kW. With a plasma aperture of 14mm and at 25kV it is capable of producing 5mA under 60 π.mm.mrad emittance. With a plasma aperture of 6mm it is capable of producing 1mA at 30 π.mm.mrad.

3. A 300cc H-/D- CUSP SOURCE

This is the second smallest ion source (figure 3) weighing only 4kg, including the 20 row Halbach array type magnets. This compact ion source is designed for neodymium ferrous N52 magnets placed on the outside of the water jacket; thus the virtual filter can be adjusted and optimized to a desired arc voltage without venting the source. It has an easily replaceable commercially available filament holder. Its compact size, simplicity and relatively low cost make it a good candidate for cyclotrons requiring up to 8mA H- current with 60 π.mm.mrad emittance. [11]

4. A 800-1200cc STANDARD CUSP SOURCE

The standard cusp source has two variations. Both of them have a 100mm diameter but vary in length. A shorter version that is 100mm long is employed in the TR13 cyclotron while a 150mm long version (figure 4) is employed in the TR25, TR30 and TR500 cyclotrons. These two ion sources are the workhorses for high current requirements. These ion sources employ a 20 row Halbach array type magnetic configuration. Four electromagnets have been built to provide virtual filter magnetic fields during the development stage so that they can be optimized to various arc voltages and different plasma conditions. During normal operation conditions it can produce up to 20mA of H- current. This source was upgraded to produce 60mA of H- beam by increasing the arc power, filament with four of 4mm diameter and 250mm long [12]. The magnetic confinement also enhanced with neodymium ferrous magnets. In this case one must increase the cooling water flow, gas flow, pumping speed. The power supplies also needed to be replaced to accommodate the increased 25kW load [12]. Transporting such a high beam current is also needed a due diligent to minimize the space charge losses. Extracted beam current versus arc current is shown in figure. 5.

5. HIGH BRIGHTNESS H- ION SOURCE

TRIUMF’s 500MeV cyclotron also has been powered by an arc discharge H- ion source that was developed in-house 30 years ago. Since then, new additions to TRIUMF, like ISAC and ARIEL have required 40% more beam from the cyclotron. Since the existing ion source was developed in 1991, the brightness is not sufficient to meet the additional beam current with the same emittance and a new ion source needed to be developed. The 1200cc ion source with strengthened magnetic confinement and a new virtual filter managed to reach the desired values. It is now capable of producing 1mA under 21 π.mm.mrad at 25kV. Figure 6 and 7 show the high brightness ion source and the emittance measurement at 1mA and 25kV [13].

6. A MICROWAVE DRIVEN H-/D- ION SOURCE

A microwave-driven H-/D- ion source has also been developed at TRIUMF to produce negative ion beams for cyclotrons and other accelerators. The source has been tested for 25kV H-/D- beam and has achieved 5 mA H- beam current with 60 π.mm.mrad emittance for 2kW of input power at a frequency of 2.45GHz. The source was operated for over one month at 2.1mA/500W without interruption for a H− beam stability test and demonstrated 2.5% stability over the period [14].

The same source was converted to produce positive ions and it is now operational in ISAC since 1995 with negligible maintenance.

Figure 1. Operational H- sources at TRIUMF

Figure 2. Smallest 125cc plasma volume H-/D- ion source developed at TRIUMF with its screw-in type filament holder.

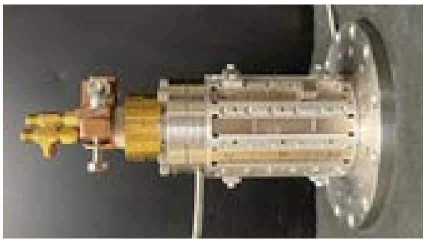

Figure 3. Second smallest 300cc plasma volume H-/D- ion source with off the shelf filament holder.

Figure 4. An ion source with 1200cc plasma Volume.

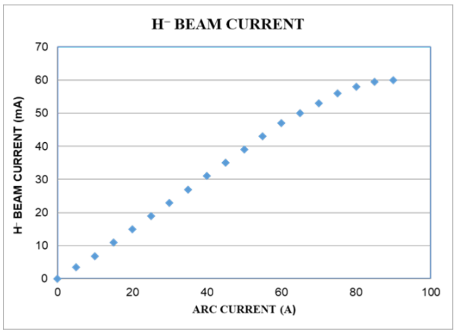

Figure 5. H- Beam current vs arc current at 140V arc voltage with enhanced magnetic field. All other parameters including hydrogen flow, PE and EE voltages were adjusted to optimize the Faraday cup current.

Figure 6. The high brightness ion source with the adjustable virtual filter.

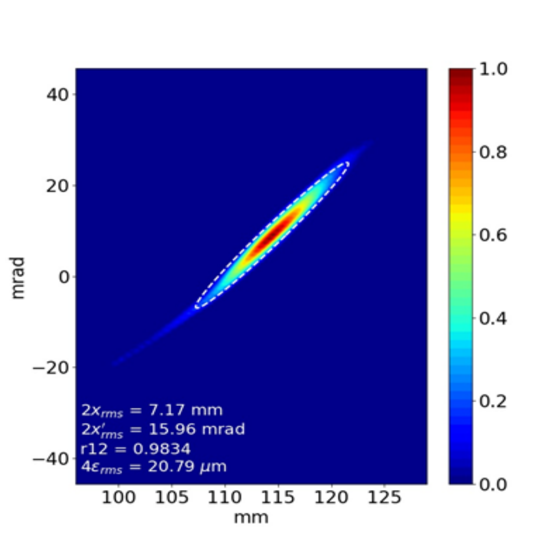

Figure 7. Emittance measurement for 1mA at 25kV

7. FILAMENT STUDIES

Tungsten based filaments (1mm to 4mm diameter) with various elemental composition were tested [12]. Since the latest filament lifetime is measured in many months, it is difficult to measure each filament life precisely up to 5A arc. Over 5A arc, 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 (figure 9). From these numbers, the filament lifetime can be extrapolated with reasonable accuracy. The filament used for highest H- current (60 mA), over 800A of filament current is needed to initiate plasma. After the plasma is ignited the filament current has to be reduced to less than 400A to achieve 90A and 140V arc due to additional filament heating by the arc power. Dedicated software/hardware is designed to stabilize 90A/140V arc instabilities. In order to produce 20mA of H- beam a single filament (blue in figure 9 – TRF200-20) is sufficient. Up to 5A of arc current, none of the filaments showed any measurable decay while the largest filament did not show any measurable decay when tested with up to 15A/100V arc. A TRF200-20 filament is now installed in the TRIUMF 500MeV cyclotron and has been running for over 6 months with 7A and 100V arc. This is the first time in the cyclotron's history that the filament could last from one shutdown to the next shutdown without needing the replacement. The same filament was installed in the TR13 cyclotron and has been running over a year at 4A and 100V arc to date.

8. EXTRACTION SYSTEMS

There were two extraction systems developed for negative ion sources: one with three electrodes (accel-accel) for well-defined energy devices like medical cyclotrons and another one with four electrodes (accel-accel-decel) for machines where variable energy is required. Both systems are equipped with electron filters in the second electrode optimized to the desired beam energy [15].

Accel-accel extraction system: Most of the negative ion sources are equipped with this type of extraction systems with higher efficiencies for fixed energy. Gaps between the electrodes can be pre-adjusted to match the desired energy. Higher the H- beam current, higher the extraction energy required in order to minimize the space charge issues during the extraction and the transmission.

Accel-accel-deccel extraction system*:* If higher currents are required with variable beam energies, a fourth electrode must be introduced. Then the source can operate at the optimum energy and the extracted beam energy can be varied from 1kV to 60kV without significant losses. Figure 10 shows the comparison of the extracted beam currents versus beam energy for both extraction systems with a standard cusp source. [15]

9. STEERING, FOCUSING AND DIAGNOSTICS ELEMENTS

In the past, combination of electromagnetic and electrostatics optical components were used in our H- transport systems. Only magnetic steering and focusing elements [16] are used in the latest TRIUMF-developed H- transport systems to minimize space charge destruction issues. Encapsulated electro magnet sheerings and permanent magnet lenses are common for fixed energies but movable (adjustable) PML is a must where variable energy is required. A permanent magnet lens which has a focal length of 250mm and adjustable range of 20kV to 30kV is shown in figure 11. An integrated Allison type emittance scanner [17] with a Faraday cup is shown in figure 12.

10. CONCLUSION

Five different H-/D- sources from 125cc to 1200cc plasma volumes were developed and tested to fulfil diverse requirements. A high brightness ion source was also developed to minimize losses in cyclotrons and achieved 1mA at 25kV under 21 π.mm.mrad. With the installation of a new high-power cathode and optimizing the virtual filter in the H- ion source, output current has been increased up to 60mA DC beam at 90A and 140V arc. The emittance was measured to be 78 mm.mrad at 20kV for the highest current extracted. Various filament configurations were also tested for different arc current ranges. The new filament design allows operation of the main H- ion source at the 500MeV cyclotron for more than six months at 7A/100V arc and more than a year at TR13 with 4A/100V arc. More detailed information and references can be found at www.ionsid.com

Figure 8. Standard 1200cc H- ion source with its 2.54GHz microwave injection system. This source also can produce any negative ions as well as positive +1 or +2 ions from gaseous or solid elements.

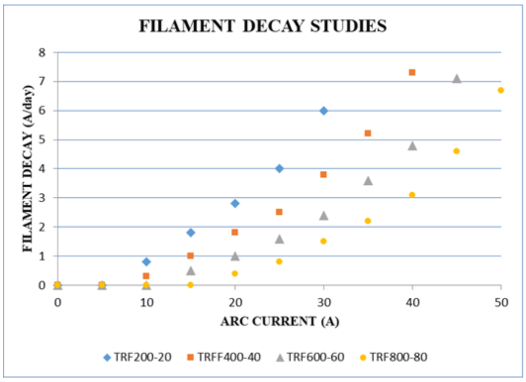

Figure 9. TR- TRIUMF, F- filament, XXX- initial arc ignition filament current, XX- suggested maximum arc current.

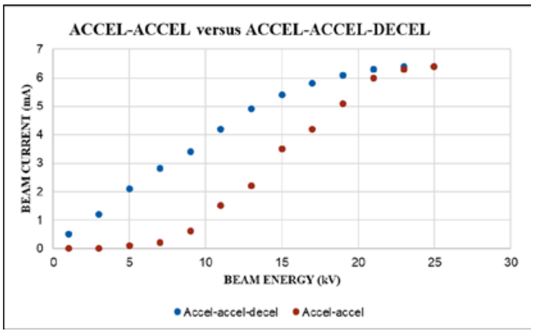

Figure 10. Red- three electrode accel-accel system. Blue- four electrode accel-accel-decel system.

Figure 11. A single ring permanent magnet lens made of neodymium ferrous N55. It is capable of focusing 20kV to 30kV.

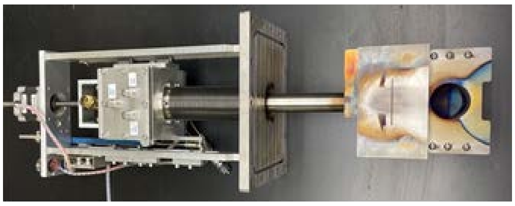

Figure 12. Integrated Faraday cup with an Allison type emittance scanner

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